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FIGURE 1. VALLEY OF PALOUSE RIVER
Just above Princeton, looking east, upstream. The meandering stream may be seen in the middle distance at the right.

FIGURE 2. VALLEY OF POTLATCH RIVER
Near Kendrick, looking downstream. The stream is about at grade. The canyon is 1500 feet deep.

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CONTRIBUTIONS TO THE GEOLOGY OF LATAH COUNTY, IDAHO

BY EDWARD L. TULLIS

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ABSTRACT

Latah County lies within the Coeur d'Alene Mountains and the Columbia Plateau. The plateau is mantled with loess which is dissected into the mature Palouse topography. The origin of the Palouse Hills is considered in relation to certain newly discovered closed depressions on the tops of some of the hills. Folding of the Clearwater monocline followed deposition of the loess and rejuvenated Potlatch River.

The mountains are underlain by metamorphosed formations of the Belt series, by rhyolite and rhyodacite flows correlated with the Seven Devils volcanics, and by the Thatuna batholith correlated with the Idaho batholith. Metamorphism of the Belt rocks was dynamothermal followed by retrograde changes. The principal intrusive rock is granodiorite grading into adamellite, tonalite, and granite. Thirty Rosiwal analyses are tabulated. The order of crystallization is normal, but quartz, microcline, orthoclase, albite, and sphene have been introduced by late replacement. Most of the granite and adamellite resulted from replacement of the other types. The Gold Hill stock is more like the igneous rocks in the Coeur d'Alene district. The principal type is syenite with considerable monzonite and syenodiorite. Dike rocks with the stock include adamellite porphyry, adamellite aplite, pyroxenite, dark syenitic pegmatite, magnetite dunite, and magnetitite.

The Columbia Plateau is underlain by Columbia River basalt. Younger flows fill valleys in the Columbia River basalt and also occur 300 feet above the plateau.

The principal economic resources are residual granitic and transported clays. The geologic conditions and mineralogy suggest weathering rather than hydrothermal origin. Certain basaltic clays resulted from hydrothermal alteration.

INTRODUCTION

GENERAL STATEMENT

Latah County, in the west-central part of the "Panhandle" of Idaho, has an area of approximately 1085 square miles.

Six and one-half months was spent in the field during the summers of 1931 and 1932. The base map was compiled from the Soil Survey map, Land Office plats, U. S. Forest Service maps, and topographic maps prepared by the writer's party. The geologic mapping was done by pacing and compass traverses, supplemented by automobile traverses.

ACKNOWLEDGMENTS

The survey was an Idaho Bureau of Mines and Geology project, and the field studies were aided by members of the staff—Dr. John W. Finch, the late Dr. F. B. Laney, Dr. A. L. Anderson, and Prof. D. C. Livingston. Mr. Walter Northby was in charge of the topographic survey and aided with the geologic mapping. Acknowledgment is due members of the staff of the Department of Geology, University of Chicago, particularly Dr. R. T. Chamberlin, Dr. J Harlen Bretz, and Dr. Albert Johannsen, for advice during the laboratory work and preparation of the report. The writer is grateful to Clyde P. Ross for critical reading of the manuscript.

PREVIOUS GEOLOGIC WORK

I. C. Russell (1897), reporting on southeastern Washington, was first to discuss the geology in the area now Latah County. Later reconnaissance work was done in the southeastern part of the county by Lindgren (1904), in the area near Moscow by Laney, Kirkham, and Piper (1923), the northern part of the county by Kirkham (1927), a large area near Moscow by Johnson and Myrene (1929), and the eastern part of the county by Anderson (1930). More than 40 additional papers describe small areas or special features.

OUTLINE OF GEOLOGY OF REGION

Much of Latah County is mountainous, summits rising to 5300 feet, but the southwestern part and the valley of Palouse River below Harvard is a plateau between 2600 and 2900 feet in elevation. The mountains are spurs and bordering ridges of the ranges of north-central Idaho underlain by Belt sediments and by batholithic and associated rocks, possibly Cretaceous. At places these rocks form isolated buttes. One of these, Potato Hill, near Deary, is underlain by Permian (?) volcanics. The plateau is the projecting fingers of the basalt fields of Washington. Locally, between and beneath the flows are middle Miocene lacustrine sediments. A thick blanket of Quaternary loess covers the plateau and the lower mountain slopes. The minor streams have intricately carved the loess into mature topography, while the major streams have cut it and basalt in deep youthful valleys, at places exposing older rocks (Table 1).

PHYSIOGRAPHY

PHYSIOGRAPHIC PROVINCES

Latah County falls within the Coeur d'Alene Mountains of the Northern Rocky Mountain Province and the Walla Walla Plateau of the Columbia Plateau Province

(Fenneman, 1931, Pl. I). The boundary, drawn at the eastern margin of the Columbia River basalt, where it invades the valleys in the prebasaltic surface (Fenneman, 1931, p. 185–186), is extremely irregular as shown by the outline of the basalt on Plate 6.

TABLE 1.—*Columnar section—Latah County, Idaho*

Age	Formation	Description
Quaternary	Alluvium	Clay, silt, sand, and gravel along present streams.
	Terrace deposits	Silt, sand, and gravel on low terraces in Palouse Hills. Silt, sand, gravel, and boulders on low and high terraces in the mountains and in the basaltic canyons.
Pleistocene	Palouse "Soil"	Loess, mantling basaltic plateau and lower mountain slopes. Thickness 0-200 feet.
Miocene or Pliocene	Younger lava	Basalt and olivine basalt at levels generally above Columbia Plateau. Thickness 0-100 feet or more.
Middle Miocene	Latah formation	Light-colored sand, silt, and clay between flows of Columbia River basalt at two principal levels. Total thickness 0-350 feet.
Miocene	Columbia River basalt	Basalt and olivine basalt forming eastern margin of Columbia plateau and partly filling ancient valleys. Thickness, exclusive of Latah formation, 0-1350 feet. Bottom not exposed at all places. Maximum thickness may reach 1650 feet.
Cretaceous (?)	Thatuna batholith	Mainly granodiorite and adamellite with important amounts of tonalite and less granite, and small masses of diorite and perthosite. Numerous aschistic and diaschistic dikes, particularly pegmatites.
	Gold Hill stock	Syenite gradational into monzonite and syenodiorite. Numerous aschistic and diaschistic dikes, those of pyroxenite being of especial interest.
Permian (?)	Volcanic rocks	Flows and flow breccias, rhyolite to dacite. Thickness 1200 feet, bottom unexposed.
Algonkian	Belt Series	Quartzite, schist, and gneiss equivalent to Wallace and older formations. Thickness 40,000 feet, bottom unexposed.

REJUVENATION OF POTLATCH DRAINAGE

The streams are of two groups: (1) those that flow southward into Clearwater River, chiefly by way of Potlatch River, and (2) Palouse River and its tributaries draining westward to Snake River. The middle and lower courses of Palouse River (Pl. 1, fig. 1) are in a valley partly filled by basalt and have low gradients.

Potlatch River also flows on basalt but has a different profile. In its upper 10 miles it falls 15 feet per mile. The gradient increases to 87 feet per mile for 16 miles between Bovill and Pine Creek and below the latter point decreases to 37 feet per mile at Juliaetta, where the canyon is 1500 feet deep (Pl. 1, fig. 2). The knickpoint near Bovill seems unrelated to structure. In the sluggish upper parts the tributaries are in Palouse loess, and the floors are terrace and floodplain deposits. In the middle

courses the streams have cut through the loess into basalt, leaving remnants of terraces. In the lower courses no terrace remnants are found in the loess high on the basaltic rims. The soil maps of Latah County (Agee, Graves, and Mickelwaite, 1917) and of Nez Percés (Agee and Peterson, 1920) and Lewis counties demonstrate the relationships. The sequence of events is clearest in the counties to the south.

South of Latah County Potlatch River is consequent on the Clearwater monocline (Russell, 1901, p. 72), where the dips of the basalt are steep (Kirkham and Johnson, 1929, p. 491–492, sta. 24). At that place the position of the stream probably is little different from that before the formation of the monocline. The profiles of the streams and relationships of the youthful canyons to the hills and flood plains of the mature Palouse topography support a hypothesis that the Potlatch drainage was rejuvenated by formation of the monocline. The effect of the folding would not have been felt immediately unless Snake River could maintain its northward course across the rising monocline near Alpowa, Washington. There is no evidence of damming there.

AGE OF THE CLEARWATER ESCARPMENT

The Palouse loess was deposited and maturely dissected before folding of the Clearwater escarpment rejuvenated the drainage. Thus the earliest age of the escarpment is fixed by the age of the loess, which is Pleistocene (Bryan, 1927). Several points of evidence indicate that the loess probably was deposited before late Pleistocene (Bretz, 1929, p. 396; Krynine, 1937; Scheid, 1940b).

ORIGIN OF PALOUSE HILLS

Description of topography.—All descriptions of the Palouse region record the unusual topography. It is mature, with relief of about 250 feet (Pl. 2, fig. 1). Many of the hills enclose northeast-facing amphitheaters, and northeastern slopes are steeper than southwestern. Most writers have emphasized the preponderance of concave slopes, with convex slopes only near the tops of hills. The flat-bottomed valleys are dry except along the larger drainage lines.

Hilltop depressions.—One unreported feature is the broad shallow depressions on the summits of some of the rare hills that have wide, flat tops (Pl. 2, fig. 2). Ten of the depressions in the southwestern part of the county are shown on Figure 1. They are circular to slightly oval with diameters of 100 to 500 yards and depths of 5 to 30 feet. The oval ones are not uniformly oriented. There is only a slight variation in elevations on the rim of any one depression, and no direction can be detected as a consistently low side on the rims. The basins contain water during the rainy season, and one of them has a permanent lake. One or two depressions reported to contain water within the previous 15 years are now drained by a narrow bottle neck along a shallow gully through the rim. Four or five other hilltops have forms gradational between closed depressions and shallow amphitheaters drained by narrow breaches.

The origin of the depressions probably is related to the origin of the Palouse soil, and recent investigators agree that this material, or at least its surface portions, is aeolian. The lack of marked elongation or consistent orientation is against formation as blow-outs. With the present amount of precipitation, a slight depression

holds sufficient moisture to prevent wind erosion. In this region, at least under present conditions, the dominant process seems to be deposition rather than erosion, except for minor shifting. Rockie (1933) suggests that the heavy-textured Palouse soil is little subject to wind erosion unless precipitation is less than 18 inches per year,

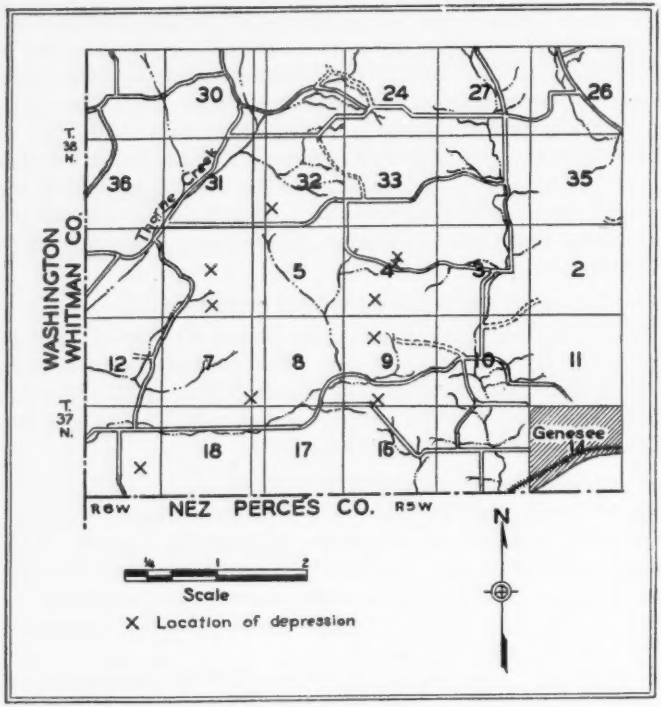

FIGURE 1.—*Map of the southwestern corner of Latah County*

Shows location of depressions on tops of Palouse Hills

and not even then unless there is no vegetation. The average annual precipitation at Moscow is about 22.5 inches.

It seems more probable that the basins resulted from inequalities of original deposition and distribution. It is difficult to know the cause of such inequalities, but perhaps it might be variation of distribution of vegetation during soil deposition, with resultant effect upon moisture content of the soil and upon local shifting by wind. The basins are on hilltops only near the highest part of the Uniontown Plateau, probably because erosion has not worked headward far enough to dissect the covering of loess completely.

Landslides.—Small landslides of the types shown in Figure 3 of Plate 2 are common on steepest slopes of the Palouse hills in the spring when the loess is saturated with water.

Origin.—Russell (1897, p. 66–67) suggested that the hills are the product of running water with modification by wind. Kirkham, Johnson, and Holm (1931), by a statistical study of orientation of amphitheaters, confirmed the fact that these face chiefly northeast, east, or north. Noting the resemblance to cirques, they proposed a snowbank nivation origin. As minor factors they recognized soil-slip, slump, mudflow, and rill erosion. The steepening of upper walls by landslides (Pl. 2, fig. 3) may be a factor not sufficiently emphasized. Study of the hilltop depressions shows that the amphitheater is encountered from the first drainage of the depressions through breaches in the rims. Orientation of the amphitheaters is random, but nivation favors perfection of those facing northeast.

METAMORPHISM OF THE BELT SERIES

GENERAL DESCRIPTION

The Belt rocks occur in two continuous but structurally separable parts of the county. The northern part includes the area from the Thatuna Hills northward, the Hoodoo Mountains, and the hills along the eastern margin north of Bovill. The structure is simple, a few major folds modified by minor folding and faulting. In the southeastern part of the county noses of large folds extend westward from Clearwater County. At least 15 isolated areas also were mapped south of the Thatuna Hills and west of Potlatch Canyon.

Eight separate formations were distinguished, but two of those in the southeastern district may be equivalent to those in the northern. They are summarized in Table 2. The Belt rocks may aggregate 40,000 feet in the northern part of the county and about 10,000 feet in the southern area.

PETROGRAPHY

Metamorphism has produced two principal types: (1) rocks containing chiefly quartz, mica, and feldspar, and (2) rocks containing chiefly quartz, diopside, or actinolite (including tremolite), feldspar, subordinate mica, and some sphene. Scapolite occurs in both but usually accompanies diopside or actinolite, and zircon and tourmaline are common in both types. The paragneiss (Table 2), gray quartzite, and most of the schist belong in the first type, while the diopside quartzite, granular quartzite, and certain layers of the schist belong in the second.

The andalusite schist that extends north and northeast from Mica Mountain to the head of the North Fork of Palouse River gives a key to the metamorphism. The rock contains numerous medium-gray, flat, irregular to diamond-shaped masses about 5 mm. thick and up to 3 cm. in diameter. In thin section the matrix resembles the schist in other parts of the formation. The gray masses are largely quartz and sericite of much finer grain than the matrix. In each gray mass are scattered ragged but optically oriented pieces of andalusite, once obviously continuous but now partly altered to quartz and sericite. In one gray mass a piece of kyanite was found, and in another section were discontinuous but optically oriented pieces of staurolite in a matrix of sericite. At many places garnet and biotite are partly altered to chlorite.

TABLE 2.—*Description of rocks of Belt Series in Latah County, Idaho*

Northern and northeastern areas

General character	Mineralogy	Relations to other formations	Distribution
Gray quartzite. Light to medium shades. Fine-grained. Well bedded, with ripple marks, Schistose in lower part. Light-gray to blue-gray argillite at places in upper part. Metamorphosed to light green at places near igneous contacts and to dark hornfels with white spots 1–1½ mm. in diameter. Total thickness probably more than 30,000 feet.	Quartz and sericite most common; biotite abundant; alkali feldspar (chiefly albite), tourmaline, zircon, and magnetite common; siderite rare. Spotted hornfels is similar in composition except that the spots are of quartz and andesine or quartz and scapolite. Muscovite and epidote may occur. The green rock consists of quartz, feldspar, and actinolite, rarely with diopside and sphene.	Top not present. Grades downward into schist.	Underlies most of the area of metamorphic rock north of Thatuna batholith and west of line connecting North Fork of Palouse River with Yale railroad station.
Mica schist. Silvery gray. Fine- to medium-grained. Thickness 4000 feet. Four hundred feet above bottom of formation is bed of andalusite schist 650 feet thick not present everywhere.	Chiefly quartz, muscovite, and biotite. Acid plagioclase, scapolite, garnet, and clinozoisite frequently occur in considerable quantity, but not universally present. Crystals of magnetite, tourmaline, and zircon generally present and locally numerous. Actinolite or tremolite abundant in some parts and at places forms metacrysts. Chlorite rare. Andalusite schist contains quartz, biotite, magnetite, chlorite, zircon, garnet partly altered to chlorite, andalusite largely altered to quartz and sericite. Cyanite and and staurolite altered to sericite are rare.	Grades upward into gray quartzite and downward into granular quartzite.	Underlies a belt 1½–5 miles wide extending northeast from Mica Mountain to county line and from there eastward to headwaters of Emerald Creek. Smaller areas occur on east slope of Beals Butte, in a triangular area between Collins and Bovill, and south of Potlatch on north side of Thatuna batholith. Complete section is exposed along North Fork of Palouse River.
Granular quartzite. White to greenish. Largely banded with green a fraction of inch to a few feet thick between thicker bands of white quartzite. Fine- to medium-grained. 5000–6000 feet thick.	Chiefly quartz with much albite and a little diopside. Green beds contain mainly quartz, albite, microcline, diopside, and tremolite. Scapolite, actinolite, calcite, and occasionally biotite, instead of diopside, are abundant. Sphene and zircon common. Allanite and olivine rare.	Grades upward into schist. Bottom not exposed.	In the Hoodoo Mountains the formation occupies crest of an anticline, with east limb on Beals Butte and west limb along upper Palouse River. Also forms east limb of syncline along east border of county.
Southeastern and southern areas			
Paragneiss. Coarse-grained silvery-gray, weathers to silvery pink or yellow. 5000 feet thick or less.	Quartz more than half the rock, plus equal amounts of muscovite and biotite. Microscopic crystals of apatite, zircon, and sphene common. Half the sections contain alkali feldspar up to 25 per cent of total. Andalusite and garnet rare.	Seems to overlie diopside quartzite with gradations. Probably faulted against granular white quartzite north of Ruby Creek. Top not discovered. Grades laterally into mixed gneiss in Bear Canyon.	Prominent ridge maker forming Tamarack Ridge and Big Bear. Underlies hills immediately surrounding Round Meadow.

TABLE 2.—*Continued*

Southeastern and southern areas

General character	Mineralogy	Relations to other formations	Distribution
Diopside quartzite. Light green. Fine- to medium-grained. At places interbedded with mica schist. 5000 feet thick or less.	Quartz and diopside most abundant. Scapolite, albite, and microcline common. Other feldspars present at places. Sphene generally occurs, zoisite and zircon often present. Calcite occurs in small amounts in many specimens. Biotite common at places. Muscovite, tremolite, olivine, and garnet rare.	Appears to rest on white crystalline quartzite and to be overlain by paragneiss.	East of Crescent along western end of Alderman's Ridge and into Three Bear Valley. Divide at headwaters of Boulder, Little Boulder, Three Bear, and Long Meadow creeks. South of Ruby Creek.
White crystalline quartzite. Massive and well jointed. Bedding not apparent. Resembles vein quartz. 100–500 feet thick.	Almost entirely quartz, cataclastic texture common. A little tourmaline, muscovite, apatite, and zircon.	Appears to underlie diopside quartzite.	Viola Ridge, Mason Butte, Tomer Butte.
Amphibolite. Black to dark green studded with pink garnets. Medium- to fine-grained.	Chiefly hornblende with abundant garnets, moderate to small amounts of quartz, and a little plagioclase, biotite, and magnetite.	Small bodies enclosed in mixed gneiss.	Cedar and Boulder valleys.
Mixed gneiss. Alternate bands of medium to coarse igneous material and of schist. Similar to parts of border of Idaho batholith to southeast. Banding not present everywhere.	Igneous bands of biotite tonalite, occasionally with hornblende instead of biotite. Sillimanite rare. Schistose bands contain quartz, biotite, muscovite, and alkali feldspar. Unbanded rock contains diopside or actinolite in addition.	Banded portions probably equivalent to paragneiss. Unbanded portions probably equivalent to diopside quartzite.	At places in bottoms of canyons of Potlatch and Little Potlatch rivers and of Dry, Bear, and Little Bear creeks.

METAMORPHISM

The quartz, mica, and feldspar type is similar to the noncalcareous rocks of the Pend Oreille district described by Gillson (1930), and the second type with quartz, diopside, actinolite, feldspar, mica, and sphene is similar to his calcareous rocks. The Latah County beds are siliceous almost throughout, and their mineralogical variation probably depends upon the ratio of calcareous or argillaceous materials to quartz in the original formations.

Possibly part of the feldspar is detrital, but the writer believes that most of it was introduced by magmatic solutions. Complete recrystallization makes the problem difficult, but the hypothesis of magmatic solutions is supported by: (1) the almost universal presence of feldspar despite its irregular distribution and variable quantity within any formation; (2) the fact that it is almost entirely alkali feldspar; and (3) the presence of other minerals believed to be secondary: tourmaline, scapolite, and zircon.

The first metamorphism was dynamothermal, the thermal element increasing in importance with time. Abundant actinolite and tremolite in several formations and remnants of cyanite and staurolite in andalusite schist attest the early importance of the dynamic element. Later, cyanite probably changed to andalusite (Harker,

1939), and staurolite to cordierite, subsequently entirely destroyed. Such changes would occur by thermal metamorphism during or just after emplacement of the batholith. Next the andalusite and staurolite (and possibly cordierite) altered to sericite and quartz, and garnet and biotite partly changed to chlorite. This "retrograde" metamorphism (Schwartz and Todd, 1941) possibly occurred during the cooling stages, perhaps fostered by magmatic solutions. Such solutions permeated widely, adding alkali feldspar, tourmaline, scapolite, and zircon.

CORRELATION

Positive correlation must await work in areas to the north and northeast, because metamorphism prevents correlation by lithology. Certainly the Wallace and possibly the Burke, Revette, and St. Regis formations are included in the gray quartzite. Their maximum thickness measured elsewhere (Umpleby and Jones, 1923, p. 7–8) is less than half the 30,000 feet estimated for the gray quartzite. Either the Coeur d'Alene section thickens to the south or younger beds are present.

The above suggests that the schist and granular quartzite in the Hoodoo Mountains are of the Prichard formation as contended by Livingston (Livingston and Laney, 1920). The white crystalline quartzite may represent another quartzitic member of the Prichard.

Possibly the paragneiss and diopside quartzite of the southeastern district may be equivalent to the schist and granular quartzite respectively, but differences make the suggestion doubtful.

PERMIAN(?) VOLCANICS

GENERAL DESCRIPTION

Two types of volcanic rocks are found in the group of hills just north of Deary. The porphyritic, light-pink, lavender, gray, and dark-purple type ranges from rhyolite to dacite and occurs at the margins of the hills except on the south. Good exposures occur on the end of the ridge northwest of Potato Hill and on the end of the ridge to the east. Occasional outcrops are found west of Vassar Meadow, along the Avon road.

The other type, a dark-purple to black flow breccia, appears to overlie the first and forms the bulk of Potato Hill. The upper part of the hill is composed of flows which dip 14° to 20° W., and the western slope is largely a dip slope. The strike varies between N. 30° W. and N. 20° E.

In addition to the large area north of Deary, there are two other small isolated outcrops: (1) an inlier in the Miocene basalt just south of Deary, and (2) the low hill within the large loop of Potlatch River a mile southwest of Bovill.

No exact thicknesses are known. The flow breccia on Potato Hill was estimated to be 950 feet thick, and the porphyritic flows possibly are 200 or 300 feet thick.

PORPHYRITIC FLOWS

There are light and dark flows. The former have pink to lavender groundmass with cream feldspar phenocrysts up to 3 mm. long, spaced at about 1½ to 2 cm. The few quartz phenocrysts do not exceed 1 mm. in diameter. The dark flows are purple to bluish gray with stony groundmass containing closely spaced light-yellow feldspar

FIGURE 1. PALOUSE TOPOGRAPHY
Looking northward from "Jain," the U.S.G.S. triangulation station in southwestern Latah County.

FIGURE 2. DEPRESSION ON TOP OF A PALOUSE HILL
The distance across the depression to the bushes on the horizon is about ¼ mile. The depression is 30 feet deep and contains a permanent lake.

FIGURE 3. LANDSLIDE
Vertical face formed at head of slide-scar is 6 feet high. Soil has slid only from the steepest part of the hill, and in the slide are numerous large unslaked chunks of loess. The amphitheater faces north.

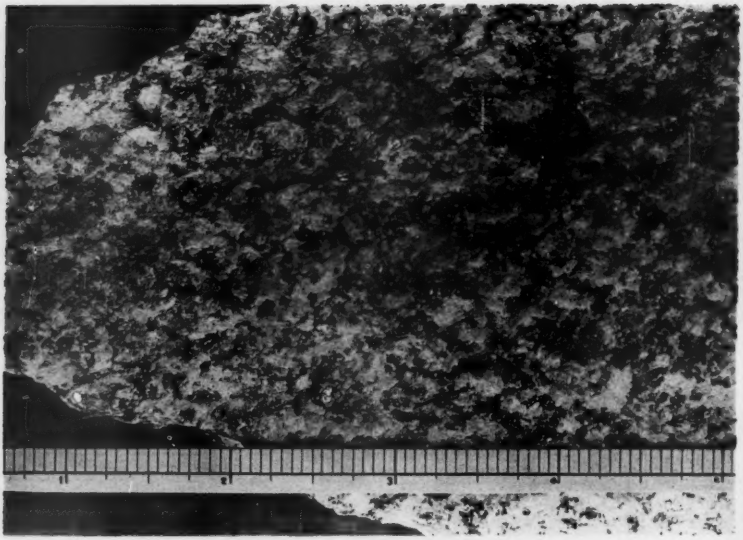

FIGURE 1. TYPICAL GRANODIORITE
From the Thatuna batholith, near Troy. Minerals are quartz, feldspar, and biotite (specimen 14, Table 4).

FIGURE 2. PORPHYRITIC ADAMELLITE
Field photograph of outcrop near Joel. Phenocrysts are microcline (specimen 24, Table 4).

TEXTURES OF PLUTONIC ROCKS

phenocrysts up to 2 mm. long. In some specimens the phenocrysts are less abundant and include quartz, glassy feldspar, and cloudy, white, or light-green feldspar.

The predominant phenocrysts are orthoclase and plagioclase, which varies from $Ab_{90}An_{10}$ to acid andesine. Most of the feldspar shows resorption (Pl. 5, fig. 1). Quartz never exceeds the feldspars. Magnetite is angular. The total quantity of phenocrysts averages about 6 per cent. The groundmass, originally hypohyaline, is devitrified. It is dominantly feldspar and quartz in ratios ranging between 3:1

TABLE 3.—*Chemical analyses of Permian(?) volcanics*

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Ignition loss	Total
No. 1	69.44	15.68	3.90	0.86	1.18	3.26	4.40	1.34	100.06
No. 2	71.68	15.06	1.90	0.38	0.34	3.04	5.74	1.72	99.86

1. Rhyodacite, Potato Hill. 2. Rhyolite, Potato Hill. Analyst: Charles Bentley, South Dakota School of Mines and Technology.

and 4:1. Feldspar is predominantly orthoclase with some acid plagioclase. Other minerals are magnetite, apatite, and zircon. Magnetite exceeds 5 per cent. The secondary minerals are white mica, kaolin, limonite, and hematite.

The flows are mainly rhyolite to dellenite and possibly dacite. One specimen each of rhyodacite and alkali rhyolite was found. Chemical analyses are required to determine many specimens. Analyses of two samples, from the ridge northwest of Potato Hill, are given in Table 3.

Specimen No. 1 is the dark rock. The norm is quartz 29.2 per cent, orthoclase 27.8 per cent, plagioclase 33.6 per cent, and femic minerals 6.0 per cent. The molecular ratio of albite to anorthite indicates andesine or oligoclase, and the microscope shows oligoclase ($Ab_{80}An_{20}$) phenocrysts. Specimen No. 2 is the light rock. The norm is quartz 31.2 per cent, orthoclase 33.9 per cent, plagioclase 26.5 per cent, and femic minerals 2.9 per cent. Molecular ratio of albite to anorthite indicates albite or oligoclase, and the microscope shows oligoclase phenocrysts. On the basis of the norms, No. 1 is rhyodacite and No. 2 is rhyolite, or both may be called dellenite.

FLOW BRECCIA

This type is purple to black, spotted with light inclusions an inch or less in average size, but ranging up to more than a foot. The dark matrix is of dense, angular inclusions, purple, black, and dark brown, cemented with the same type of material. The dark inclusions in turn contain others. Both matrix and dark inclusions have a few phenocrysts of feldspar, up to 3 mm. long, and round phenocrysts, or inclusions of quartz.

The microscope shows about half the volume to be unbrecciated glassy matrix. The larger inclusions are fragments of breccia cemented with glass. The other inclusions are fragments of sedimentary and igneous rocks. The matrix bears little resemblance to the porphyritic rhyolite flows. Except for globulites and a few spherulites, the groundmass is almost entirely cryptocrystalline. One flow may be dacite, suggested by abundant hornblende in the groundmass. Variation in index

of refraction of the devitrified glass indicates considerable range in composition. All of the rocks are quartz-bearing.

CORRELATION AND AGE

No exact age determination can be made. They are younger than pre-Cambrian metamorphic rocks and older than the Cretaceous (?) batholith. On a reconnais-

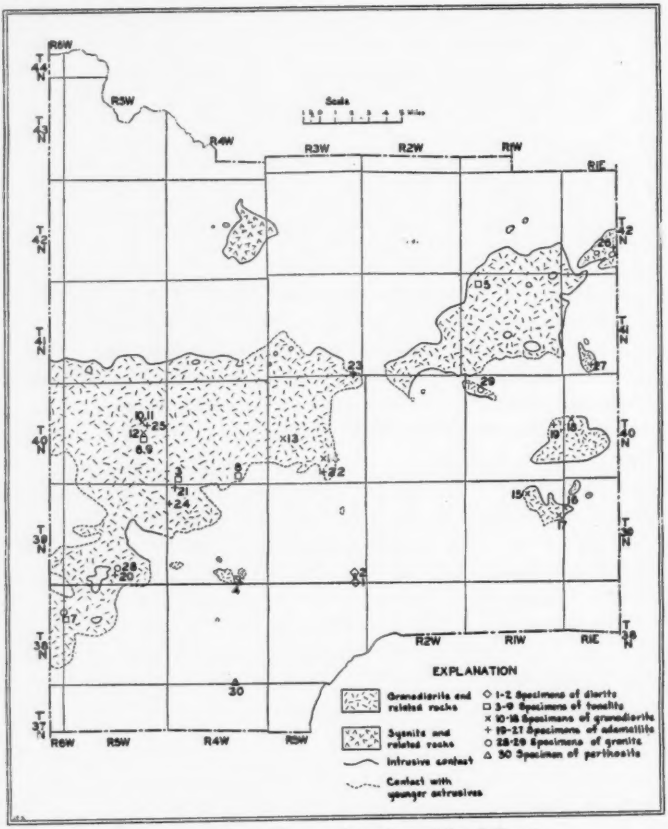

FIGURE 2.—*Map of igneous intrusions of Latah County*
Shows distribution of analyzed specimens

sance map of the Clearwater region Anderson (1930) shows the rocks by the same symbol as the Permian Seven Devils volcanics.

CRETACEOUS(?) INTRUSIVE ROCKS

GENERAL STATEMENT

The plutonic rocks are: (1) quartz-bearing, the dominant type, chiefly granodiorite plus important amounts of adamellite and tonalite and minor amounts of granite;

(2) quartz-free, or nearly so, including syenite and more basic types. The first type is found in the Thatuna batholith and as stocks in the southeastern area. Two small areas of diorite and perthosite are shown by the same map symbol. The second type occurs only in the Gold Hill stock (Fig. 2).

THATUNA BATHOLITH

Extent.—A large area of intrusive rock extends across the county through the Thatuna Hills and Paradise Ridge and over the State line to Bald Butte, Washington. The area in Idaho is about 212 square miles, and the exposure probably was 30 to 50 per cent greater before extrusion of the basalt. Since the plutonic mass is many miles from and independent of the Idaho batholith, it is here called the Thatuna batholith.

Granodiorite and related rocks.—The Thatuna batholith is essentially uniform in composition over large areas, but as a whole is far from constant. Granodiorite, adamellite, tonalite, and granite each make considerable masses and form the principal intrusions. Of the many specimens collected from the batholith and stocks, 29 were studied microscopically, excluding hypabyssal bodies and the Gold Hill stock, described in later sections. The locations of the specimens are shown in Figure 2.

The typical light-gray rock is shown in Figure 1 of Plate 3. Many specimens, particularly those of adamellite, contain less than 5 per cent dark minerals and frequently are cream or almost white. The texture is granular but may be gneissic or porphyritic (Pl. 3). Most of the visible grains are between 1 mm. and 5 mm., averaging a little more than 2 mm. The stocks south of Bovill and north and east of Park are medium- to fine-grained, averaging about 1.5 mm. Phenocrysts vary from 3 mm. to more than 3 cm. but average about 2 cm. Megascopically the principal minerals are quartz, feldspar, and biotite. Muscovite often occurs, and occasionally garnet and epidote. Hornblende is common only in quartz-free types. Sphene and tourmaline are rare except microscopically.

The mineralogical composition, determined by the Rosiwal method, is given in Table 4, and the positions of the rocks on a Johannsen (1939) triangular diagram are shown in Figure 3. Field observations show that granodiorite is dominant. Averages of the three principal families are the last three rocks in Table 4.

Diorite.—Diorite forms the southern half of an inlier along Bear Creek southwest of Atwater Lake. The exposure is stained reddish-brown, but fresh specimens show light cream-colored plagioclase speckled with green hornblende. The grains range between 1 and 3 mm. Two specimens (Nos. 1 and 2) are included in Table 4 and Figures 2 and 3.

Perthosite.—Perthosite (Phemister, 1926) crops out as an inlier near Pine Grove School between Genesee and Juliaetta. It is light cream-colored and medium-grained, with feldspar crystals up to 5 mm. but averaging 1½ mm. The texture is xenomorphic-granular (Pl. 4, fig. 2). Microcline-microperthite and cryptoperthite dominate accessory magnetite and apatite and a few small segregations of a ferromagnesium mineral, altered beyond recognition. Microcline-microperthite shows albite ($Ab_{96}An_6$) in spindles and as ramifying veinlets. Rosiwal analysis shows the ratio of potash feldspar to visible albite in the microcline-microperthite to be 2:1.

Origin of rock types.—In most of the rocks the order of crystallization is constant. First minerals are magnetite, apatite, and zircon. Most of the augite has been converted to hornblende. Hornblende and plagioclase are partly contemporaneous. Biotite overlaps hornblende, and potash feldspar and quartz are later than biotite. Generally microcline formed after all other minerals (Pl. 4, fig. 1) but at places is older than quartz.

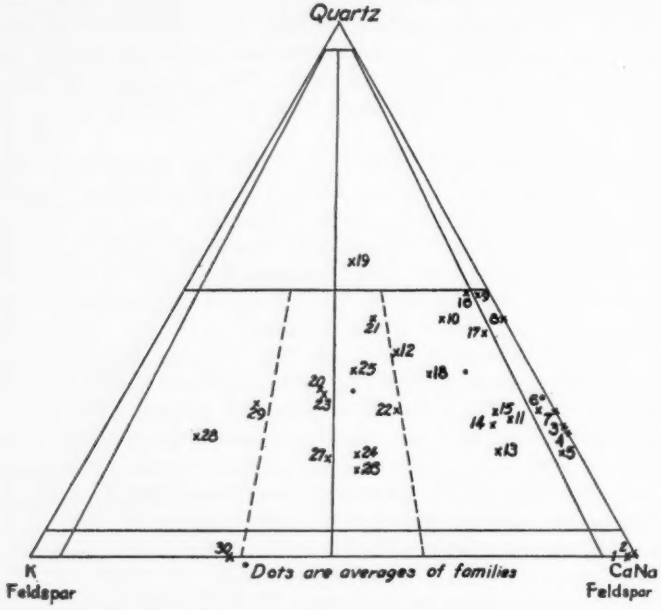

FIGURE 3.—*Triangular diagram of modes of plutonic rocks*
Plotted according to Johannsen's system

Anderson and Hammerand (1940) have described intensive endomorphism in a few square miles on Paradise Ridge. Hornblende-biotite diorite has been hydrothermally converted to biotite-quartz diorite and granodiorite. The textural evidence they describe is duplicated in the writer's specimens.

In most of the Thatuna batholith the chief late replacement minerals are quartz and microcline (Pl. 4, fig. 1) with less orthoclase and albite and scattered sphene. Microcline, orthoclase, and quartz replace all minerals, but microcline particularly attacks plagioclase and biotite. It is difficult to estimate how much microcline formed by replacement, but textural evidence suggests that most of it did.

Tonalite and granodiorite appear to be parts of the batholith as it originally solidified, except locally as on Paradise Ridge. The principal potash feldspar is orthoclase, mostly pyrogenic. The ratio of microcline to orthoclase is less in tonalite and granodiorite than it is in adamellite and granite (Table 4, analyses 31–33). The latter rocks have formed by replacement of the former by microcline.

TABLE 4.—*Volumetric modes of plutonic rocks of Latah County*

	1	2	3	4	5	6	7	8	9	10	11
Quartz	.....	0.6	22.1	21.9	19.1	23.0	24	38.2	38.7	42.7	22.6
Andesine	48.2	.....	68.3	70.2	.....	58.8	65	47.2	.....	.....	.....
Oligoclase	.....	.....	.....	.....	72.9	.....	.....	.....	38.4	.....	52.3
Albite	2.7	1.1	.....	.....	.....	.....	.....	.....	.....	37.4	.....
Antiperthite	35.0	89.4	.....	.....	.....	.....	.....	.....	9.9	.....	2.4
Microcline	x	.....	.....	.....	.....	1.9	.....	.....	2.0	1.5	6.9
Microcline-microperthite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Cryptoperthite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Orthoclase	1.1	x	x	.....	2.6	0.5	.....	.....	0.3	5.5	0.5
Microperthite	.....	.....	.....	.....	.....	.....	.....	.....	.....	3.0	.....
Biotite	x	0.7	7.2	4.7	0.5	14.2	9	10.0	7.2	.....	5.1
Muscovite	.....	.....	1.1	2.5	.....	0.2	1	2.2	0.4	3.8	6.0
Hornblende	10.7	6.5	.....	.....	1.6	0.3	.....	.....	x	.....	.....
Augite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Magnetite	x	.....	x	x	x	0.3	x	.....	0.3	.....	x
Apatite	.....	0.1	x	0.4	x	x	x	x	x	x	x
Sphene	1.2	0.1	.....	.....	0.1	0.9	x	.....	0.2	.....	.....
Zircon	x	x	x	0.1	0.1	.....	x	x	x	x	x
Monazite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Garnet	.....	.....	.....	x	x	.....	.....	.....	x	.....	.....
Ilmenite	.....	.....	.....	.....	.....	.....	.....	x	.....	.....	.....
Rutile	.....	.....	.....	.....	.....	.....	x	x	.....	.....	.....
Allanite	x	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Tourmaline	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Secondary white mica	.....	x	x	.....	x	x	x	0.8	0.3	6.1	4.2
Kaolin	x	x	x	x	x	x	x	x	x	x	x
Epidote	0.1	1.5	1.3	.....	0.3	x	x	.....	2.2	x	.....
Chlorite	.....	.....	x	0.2	x	x	.....	1.5	x	.....	x
Limonite	.....	.....	x	.....	x	.....	.....	.....	.....	.....	.....
Hematite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcite	.....	.....	.....	.....	.....	0.2	.....	.....	0.4	.....	.....
Zoisite	0.6	.....	x	.....	x	x	.....	.....	.....	.....	.....
Leucoxene	.....	.....	.....	.....	.....	.....	.....	x	.....	.....	.....

	12	13	14	15	16	17	18	19	20	21	22
Quartz	37.9	16.1	22.8	25.3	43.6	38.2	32.0	49.7	28.9	38.3	27.4
Andesine	.....	53.9	.....	57.6	41.3	48.4	45.2	.....	29.2	28.9	.....
Oligoclase	36.1	.....	58.7	.....	.....	.....	.....	22.4	.....	.....	46.2
Albite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Antiperthite	.....	.....	.....	.....	.....	.....	.....	.....	.....	3.4	.....
Microcline	5.8	.....	4.1	8.7	3.3	.....	.....	16.2	32.5	15.5	19.0
Microcline-microperthite	.....	.....	.....	.....	.....	.....	.....	.....	.....	3.3	.....
Cryptoperthite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Orthoclase	8.0	10.3	2.3	0.6	.....	3.3	16.1	1.6	1.3	2.2	6.5
Microperthite	6.4	.....	4.1	.....	.....	.....	.....	.....	x	.....	.....
Bictite	0.3	9.8	5.1	5.3	10.1	7.9	4.9	9.4	6.8	4.4	x
Muscovite	2.1	.....	2.6	1.0	0.4	1.7	1.0	0.7	1.0	3.9	0.1
Hornblende	.....	6.8	.....	.....	.....	.....	.....	.....	.....	.....	.....
Augite	.....	0.3	.....	.....	.....	.....	.....	.....	.....	.....	.....
Magnetite	.....	1.3	x	x	x	x	0.3	.....	0.2	x	.....
Apatite	x	1.4	x	0.4	0.2	0.1	0.5	x	x	.....	x
Sphene	.....	.....	.....	x	x	.....	x	.....	.....	x	.....
Zircon	.....	x	x	x	0.1	x	.....	x	.....	x	.....
Monazite	.....	.....	.....	x	x	0.2	.....	x	.....	.....	.....
Garnet	.....	.....	.....	.....	.....	.....	.....	.....	x	.....	.....

TABLE 4.—*Continued*

	12	13	14	15	16	17	18	19	20	21	22
Ilmenite					x						
Rutile											
Allanite											
Tourmaline					x						
Secondary white mica	1.5		0.3	x		x	x	x		x	0.9
Kaolin	x	x	x	x	x	x	x	x	x	x	x
Epidote	1.2				0.1		x			x	
Chlorite	x		0.1	1.0	0.5	x					
Limonite							x			x	x
Hematite											
Calcite	0.7				x						
Zoisite				0.2		0.2				x	
Leucoxene											

	23	24	25	26	27	28	29	30	31	32	33
Quartz	30.1	17.4	29.3	18.5	16.9	21.8	27.9		29.4	31.2	26.7
Andesine	32.1				36.1		22.3				62.0
Oligoclase		39.6	29.6	8.9		14.5			35.2	48.1	
Albite											
Antiperthite				34.7		1.1					
Microcline	25.0	2.9	12.8	27.0	0.8				23.8	3.3	0.5
Microcline-microperthite	8.4	29.7	13.3	9.4		59.1		99.9			
Cryptoperthite											
Orthoclase		0.3	1.3	0.6	37.3		46.4		6.0	6.7	0.5
Microperthite	1.7										
Biotite	1.1	0.2	2.1	x	4.6	0.1	x		3.2	5.4	7.7
Muscovite	1.7		7.5			x	x		1.7	2.1	1.1
Hornblende		5.7		2.1	1.2				1.0	0.8	0.3
Augite											
Magnetite	x	0.4	x		2.6		3.3	x			
Apatite		0.7			0.4	x		x			
Sphene		0.7									
Zircon	x	x	x	x	x	x	x				
Monazite											
Garnet											
Ilmenite						x					
Rutile											
Allanite											
Tourmaline											
Secondary white mica	x		3.0			3.3	x	x			
Kaolin	x	x	x	x	x	x	x	x			
Epidote		x									
Chlorite			1.1								
Limonite		x				x	x				
Hematite								x			
Calcite			x								
Zoisite											
Leucoxene						x					

1. Diorite. Bottom of valley of Bear Creek. SW. ¼ sec. 36, T. 39 N., R. 3 W.
2. Diorite. Same locality as 1.
3. Gneissic tonalite. SW. ¼, SE. ¼ sec. 31, T. 40 N., R. 4 W.
4. Tonalite. S. ½, SW. ¼ sec. 35, T. 39 N., R. 4 W.
5. Leucotonalite. W. Fk. of Potlatch Ck., S. of Beals Butte. SW. ¼ sec. 5, T. 41 N., R. 1 W.
6. Tonalite. Dump of White Cross Mine. SE. ¼ sec. 14, T. 40 N., R. 5 W.
7. Biotite tonalite. Bald Butte Ridge. Hoffman, analyst: Jour. Geol., vol. 40 (1932) p. 643–644.

(*Continued at bottom of next page*)

Contact relations and exomorphism.—Contact relations of plutonic rocks and the Belt formations vary with location and type of rock invaded. In the central and northern parts of the county the type of quartzite determines the nature of the contact. In extremely fine-grained types, such as the gray quartzite, the contact is sharp and follows joint planes, but the contact with the granular quartzite is so gradational that it must arbitrarily be placed within limits that vary within several hundred yards. By increase of feldspar, the quartzite grades into igneous rock. The most extensive example is along the east-west divide between Potlatch drainage and Palouse River and Emerald Creek, in the center of T. 42 N., R. 1 W.

To the south along Potlatch and Little Potlatch drainageways, thin layers of pegmatite and aplite are interbanded with paragneiss and diopside quartzite, forming extensive masses of banded gneiss, described in Table 2. By increase in igneous material, banded gneiss grades into igneous rock containing scattered thin layers of schist, seen along the highway north of Troy vill. The belt of banded gneiss, seen in scattered inliers in the basaltic canyons, is 12 miles wide in Latah County and extends, with some interruptions, for another 15 miles to the southeast into Clearwater County where it borders the Idaho batholith (Anderson, 1930, p. 28–29; Pl. 7). In contrast, the Thatuna batholith has only a thin zone of banded gneiss or none at all. Except where banded gneiss occurs, the contact of batholith and schist is sharp. The banded gneiss to the southeast and the increase of metamorphism in that direction indicate a large intrusion, possibly the Idaho batholith, at no great depth beneath the southeast corner of Latah County.

HYPABYSSAL ROCKS

General statement.—At many places the plutonic rocks are bordered by apophyses little different in texture and composition from the main intrusions. A common variation is the almost complete absence of dark mineral. Rocks with the common

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8. Tonalite. Near Troy. SW. ¼ sec. 35, T. 40 N., R. 4 W.
9. Tonalite. White Cross Mine. SE. ¼ sec. 14, T. 40 N., R. 5 W.
10. Leuco-sodaclase-granodiorite-gneiss. Dump of abandoned tunnel. NE. ¼ sec. 14, T. 40 N., R. 5 W.
11. Granodiorite. Same locality as 10.
12. Leucogranodiorite. Same locality as 6.
13. Granodiorite. N of Troy. Near E. ¼ cor., sec. 19, T. 40 N., R. 3 W.
14. Granodiorite. Sec. 27, T. 40 N., R. 3 W.
15. Granodiorite. NW. of Park. SW. ¼, SE. ¼ sec. 3, T. 39 N., R. 1 W.
16. Granodiorite. W. ½, SE. ¼ sec. 7, T. 39 N., R. 1 E.
17. Granodiorite. Near center of NE. ¼ sec. 13, T. 39 N., R. 1 W.
18. Granodiorite. Near center of E. ½ sec. 18, T. 40 N., R. 1 E.
19. Quartz adamellite. Bottom of valley of Ruby Ck. SW. ¼ sec. 13, T. 40 N., R. 1 W.
20. Adamellite gneiss. Paradise Ridge.
21. Leucoadamellite. Near S. ¼ cor., sec. 31, T. 40 N., R. 4 W.
22. Leucoadamellite. Sec. 34, T. 40 N., R. 3 W.
23. Leucoadamellite. Along Harvard-Deary road in sec. 36, T. 41 N., R. 3 W.
24. Porphyritic adamellite. N. ½, NW. ¼ sec. 7, T. 39 N., R. 4 W.
25. Leucoadamellite. Same locality as 10.
26. Leucoadamellite. Near Sherwin where highway crosses county line. Sec. 27, T. 42 N., R. 1 E.
27. Adamellite. NW. ¼ sec. 32, T. 41 N., R. 1 E.
28. Leucogranite. NW. ¼, NW. ¼ sec. 34, T. 39 N., R. 5 W.
29. Leucogranite. Near intrusive contact on E. side of Potato Hill.
30. Perthosite. NW. ¼ sec. 2, T. 37 N., R. 4 W.
31. Adamellite. Average of nine specimens listed as 19–27 above. Oligoclase averages $Ab_{78}An_{22}$.
32. Granodiorite. Average of nine specimens listed as 10–18 above. Plagioclase is sodic andesine in most specimens but averages $Ab_{74}An_{26}$.
33. Tonalite. Average of seven specimens listed as 3–9 above. Andesine averages $Ab_{62}An_{38}$.

texture and structure of hypabyssal rocks include granodiorite porphyry, gradational to adamellite porphyry, granite porphyry, and diorite porphyry. Pegmatites, aplites, and lamprophyres are common.

Granodiorite porphyry and related rocks.—Porphyritic dikes are most abundant east and south of Bovill. Two localities have special textural varieties: (1) the bottom of Dry Creek in sec. 11, T. 39 N., R. 3 W., more than a mile above its mouth; (2) Corral Creek on the northwest side of Cherry Knob. A few dikes occur near the Hatter Creek road south of Princeton. Microscopically most of the rocks are granodiorite porphyry. Megascopically a typical rock is medium gray but may be greenish gray. The groundmass is fine to stony, and phenocrysts generally are 1 to 2 mm. The most common phenocrysts are biotite and light laths of plagioclase, but hornblende occurs at places.

Compositions are given in Table 5 (Nos. 1 and 2). The rock from Dry Creek (No. 1) is typical of most of the granodiorite porphyry in that phenocrysts form a large part of the rock, and the groundmass is very fine (Pl. 4, fig. 3). Table 6 gives the proportions of the principal minerals in phenocrysts and groundmass. In the rock from Corral Creek phenocrysts are few, and their diameters are only about three times those of crystals in the groundmass.

A rare example of granodiorite porphyry with groundmass too fine to determine occurs on a tributary of Potlatch Creek a mile east of Cornell. The rock is white and contains less than 5 per cent dark minerals. Light cream-colored feldspar phenocrysts are in a groundmass of feldspar microlites cemented by quartz grains 0.1 mm. in diameter. The principal minerals are oligoclase ($Ab_{83}An_{17}$), quartz, orthoclase, and microcline. Magnetite is accessory, and zoisite and white mica are secondary. A partial chemical analysis by Charles Bentley, Analyst of the Mining Experiment Station, South Dakota State School of Mines, shows: 77.24 per cent SiO_2, 1.06 per cent Fe_2O_3, 13.38 per cent Al_2O_3, 0.40 per cent CaO, 0.56 per cent MgO, 3.26 per cent K_2O, 3.94 per cent Na_2O, 0.90 per cent loss on ignition. The norm is 39.9 per cent quartz, 35.5 per cent plagioclase ($Ab_{90}An_{10}$), 19.5 per cent potash feldspar, 2.5 per cent mafic minerals.

Granodiorite porphyry grades through light-gray adamellite porphyry into cream and chalk-white granite porphyry resembling extrusive rock and seldom containing more than 3 or 4 per cent of dark mineral.

Aplites and pegmatites.—The aplites have typical texture, but some grade toward the coarser granitic rocks that form many apophyses of the batholith. The chief minerals are quartz, potash feldspar (microcline, orthoclase, or microperthite), and plagioclase, usually oligoclase. Plagioclase usually exceeds 5 per cent. Small amounts of biotite and muscovite are common, and magnetite, apatite, zircon, and garnet are accessory. Most of the specimens are granite aplite, but small dikes of diorite aplite (No. 3, Table 5) were found three-quarters of a mile south of Bovill.

Descriptions of the granite pegmatites near Avon have been given by Shannon (1922), Sterrett (1923), Anderson and Piper (1924), Anderson (1933), Campbell (1939), Scheid and Allen (1940), and Forrester (1942). Simple pegmatites without the rare minerals found at Avon are abundant in all parts of the Thatuna batholith and at many places just outside its margin.

TABLE 5.—*Volumetric modes of hypabyssal rocks of Latah County*

	1	2	3	4	5
Quartz	19.1	11.7	.....	4.2	8.2
Orthoclase	16.5	24.6	1.4	.....	.....
Albite	.....	4.0	.....	60.9	.....
Oligoclase	.....	.....	97.1	.....	.....
Andesine	51.5	47.9	.....	.....	.....
Labradorite	.....	.....	.....	.....	49.6
Biotite	11.4	9.6	.....	x	.....
Hornblende	1.5	0.7	x	4.2	0.1
Augite	.....	x	1.5	.....	4.5
Magnetite	x	1.0	.....	2.7	3.6
Apatite	x	0.2	x	0.8	2.2
Zircon	x	x	.....	.....	.....
Pyrite	x	.....	.....	.....	.....
Chlorite	x	x	.....	20.4	15.6
Epidote	.....	.....	.....	6.4	2.3
Kaolin	x	x	x	x	x
Secondary white mica	.....	x	.....	0.3	0.1
Calcite	.....	x	.....	x	0.4
Limonite	x	x	.....	x	.....
Hematite	.....	.....	.....	x	.....
Remainder	.....	.....	.....	.....	13.4*

* Includes 12.3 per cent of microcryptocrystalline spherulitic material probably consisting of quartz and an alkali feldspar.

1. Granodiorite porphyry from Dry Creek, near center of sec. 11, T. 39 N., R. 3 W.
2. Granodiorite porphyry from Corral Creek, in N. ½ sec. 1, T. 40 N., R. 2 W.
3. Leucodiorite aplite, near Bovill, in NE. ¼, NE. ¼, sec. 1, T. 40 N., R. 1 W.
4. Lamprophyre, Bovill-Elk River highway, near center of sec. 18, T. 40 N., R. 1 E.
5. Lamprophyre, just west of county line near Ruby Creek Mine.

TABLE 6.—*Mineralogical composition of granodiorite porphyry from Dry Creek*

Mineral	Phenocrysts	Groundmass	Total
Quartz	1.2	17.9	19.1
Andesine	49.7	1.8	51.5
Orthoclase	0.0	16.5	16.5
Biotite	4.0	7.4	11.4
Hornblende	1.5	0.0	1.5
Total	56.4	43.6	100.0

Lamprophyres.—Lamprophyre dikes are numerous in the southeast part of the county. The fresh rocks are dark gray to dark green. Many dikes are not porphyritic, or, if they are, the phenocrysts are plagioclase instead of dark mineral. The microscopic texture resembles diabasic, but plagioclase laths have ragged outlines (Pl. 4, fig. 4). The average grain size is between 0.5 and 0.75 mm.

The composition is closest to spessartite, but few dikes are typical spessartite. The principal mineral is plagioclase—albite in some rocks and labradorite in others, but andesine in most. The chief dark mineral is brown hornblende or microscopically colorless augite, altered to chlorite and epidote. Secondary calcite is common, and magnetite and apatite are abundant. The quartz content is high enough to place most of the dikes in the tonalite family, and the content of dark mineral is a little less than normal in lamprophyre (Nos. 4 and 5, Table 5). Such rocks might be termed quartz spessartite. Specimens 4 and 5 represent extremes. Albite in No. 4 has the composition $Ab_{95}An_5$, and plagioclase in No. 5 ranges from andesine ($Ab_{57}An_{43}$) to labradorite ($Ab_{40}An_{60}$) within single crystals with average about $Ab_{47}An_{53}$.

GOLD HILL STOCK

General statement.—The syenite and related quartz-poor rocks of Gold Hill (Stewart, 1914; Faick, 1937), north of Princeton, differ sufficiently to deserve separate discussion. The stock occupies $6\frac{1}{2}$ square miles, and two small outliers occur in the bottoms of Hoteling and Gold creeks. The porphyritic border phase crops out in a railroad cut east of Princeton 2 miles south of the main contact.

The main intrusion is variable. The dominant type appears to be syenite, but considerable masses of monzonite and syenodiorite occur. Among the border rocks adamellite is common, but much granodiorite is found, and also syenite, albite syenosyenodiorite, and tonalite. Many dikes of adamellite porphyry occur, and aplite and pyroxenite are the most common diaschistic rocks. Pyroxenite grades into pegmatitic dark syenite and granite on one hand and into dunite and magnetitite on the other.

Description and origin of hornblende syenite.—Many outcrops along roads at the west side of Gold Hill show transition to the border phase. The central intrusive of typical hornblende syenite and subordinate hornblende monzonite and hornblende syenodiorite is accessible by foot trails.

The hornblende syenite and related plutonic rocks are gray. The texture is equigranular, transitional to porphyritic. The most abundant minerals are irregular to stubby prisms of light-gray potash feldspar and white to cream-colored plagioclase, and dark-green hornblende. Most grains are between 1 mm. and 2 mm., but hornblende is up to 5 mm. Phenocrysts are pink to gray microcline up to 2 cm. Small crystals of sphene and of light-green pyroxene are abundant.

Microscopically (Pl. 4, fig. 5) potash feldspar generally exceeds plagioclase 2:1. No. 1 in Table 7 is a Rosiwal analysis. Plagioclase is sodic oligoclase, $Ab_{90}An_{10}$ to $Ab_{80}An_{20}$, but Faick reports andesine also. Augite is faintly green suggesting presence of the aegirite molecule. Magnetite, sphene, and apatite are more abundant and in larger crystals than in the Thatuna batholith, while zircon is rarer.

Allowing for overlap, the order of crystallization is: accessory minerals, augite, hornblende, plagioclase, potash feldspar, and quartz. Automorphic crystals of sphene which form inclusions and cut boundaries of other minerals may be late replacements.

Microcline and, to a lesser extent, quartz have "replaced" plagioclase about the margins of crystals. Faick (1937, p. 14–18) concluded that the replacements have

converted an original quartz diorite (found at places in the border of the stock) into the present syenite. The writer has estimated that the plagioclase removed probably did not exceed 20 per cent of that now present. Substitution of the limited

TABLE 7.—*Volumetric modes of rocks from Gold Hill*

	1	2	3	4
Quartz	0.6	12.9	10	.....
Orthoclase	6.4	4.7	.....	.....
Microperthite	2.0	6.7	.....	.....
Microcline	7.7	4.5	.....	.....
Microcline-microperthite	35.0	21.9	.....	.....
Albite	.....	.....	.....	1.7
Oligoclase	26.5	.....	.....	.....
Andesine	.....	38.2	65	.....
Hornblende	11.4	4.9	15	1.2
Augite	5.4	1.7	5	74.3
Biotite	.....	x	.....	7.3
Magnetite	2.0	2.8	.....	.....
Ilmenite	.....	.....	.....	10.7
Sphene	1.5	1.0	.....	1.6
Apatite	x	0.5	.....	3.2
Zircon	x	0.1	.....	.....
Epidote	1.4	.....	.....	0.1
Secondary white mica	0.1	x	.....	.....
Kaolin	x	x	.....	x
Carbonate	.....	x	.....	x
Chlorite	.....	x	.....	.....
Remainder	.....	.....	5*	.....

* Includes microcline, orthoclase, and accessory minerals.
1. Hornblende syenite from Gold Hill.
2. Porphyritic adamellite from the southern border of Gold Hill.
3. Quartz diorite (tonalite) from margin of Gold Hill. Faick (1937, p. 14), analyst.
4. Biotite-ilmenite pyroxenite from Gold Bug Mine.

amount of plagioclase apparently removed would not be enough to change the present rock from syenite or monzonite. As for the original rock having been quartz diorite, the writer has found no evidence of replacement of quartz by microcline, but rather has found quartz embaying plagioclase.

Porphyritic adamellite and other border rocks.—Most of the border is porphyritic and variable in appearance. One of the most common rocks, porphyritic adamellite, is exposed on the west and south sides of Gold Hill, for example, in the railroad cut east of Princeton. Other types, including granodiorite, albite syenodiorite, quartz diorite, and porphyritic syenite occur in the mines at the headwaters of Jerome Creek on the east side of Gold Hill, at the Carrico tunnels, and along the tributaries of Gold Creek on the west side. Some of the rocks are large dikes but have plutonic texture. Table 7, No. 2, is a Rosiwal mode of typical porphyritic adamellite.

Quartz diorite (Table 7, No. 3) has been described by Faick (1937, p. 14–15). It resembles syenite but contains quartz. It is porphyritic in part and locally is granodiorite. Albite syenodiorite, at the Gold Bug Mine, is light pink and contains segregations, up to more than an inch across, of green hornblende.

Description and origin of ultrabasic rocks.—Ultrabasic dikes occur along the tributaries of Jerome Creek and near the head of Hoteling Creek. There are several distinct types—pyroxenite, dark syenitic pegmatite, magnetite dunite, and magnetitite—but these are gradational. Dark-green, fine- to medium-grained pyroxenite is the most common. It is equigranular but may have phenocrysts of pyroxene up to 3 mm. long and so resemble lamprophyre. Typical pyroxenite (Table 7, No. 4) is dominantly augite, colorless to light green suggestive of aegerine. At places the color suggests presence of titanium. Microcline may take the place of all or part of the albite. Ilmenite is rimmed with sphene (Pl. 4, fig. 6).

Pyroxenite grades to dark syenite, which at the Gold Bug Mine is pegmatitic and contains medium-green augite, black biotite partly altered to golden brown, and medium-gray feldspar, all generally measuring between 2 and 4 cm. but at places more than 12 cm. Magnetite, sphene, pyrite, and chalcopyrite grains are not larger than $\frac{1}{4}$ cm. Feldspar content may approach 50 per cent. Microcline exceeds albite in the rocks with a high percentage of feldspar but in other specimens albite may be the only feldspar. At places the pegmatite contains enough quartz to be granite.

Many specimens of pyroxenite at the head of Hoteling Creek contain exceptionally abundant magnetite, and some specimens classed as magnetite dunite contain olivine instead of augite. The texture of dunite is irregular, with olivine concentrated in patches and streaks through magnetite. Dunite grades into magnetitite which is never entirely free of olivine. No gradation between pyroxenite and dunite was found. Fresh specimens are only on prospect dumps, so field relations were not determined.

Order of crystallization in pyroxenite and pegmatite is: (1) augite, (2) apatite, (3) biotite and hornblende, (4) ilmenite and magnetite partly simultaneous with biotite and hornblende and partly later, (5) sphene, (6) albite, microcline, and quartz. Biotite and hornblende replace augite, and microcline replaces biotite extensively but augite only slightly.

On Hoteling Creek ultrabasic rocks occupy a linear zone about a quarter of a mile long three-quarters of a mile inside the stock. This may indicate that they were intruded along fractures cutting the stock.

Faick (1937, p. 13) suggested that the ultrabasic rocks are older than the syenite and that the pegmatite resulted from metamorphism of the ultrabasic rocks by the syenite. Instead, it appears that the pegmatite is a primary phase of a basic intrusion. As such the pegmatite is the product of the final magmatic stage of an intermediate magma of which the pyroxenite and related rocks were a differentiated residual. This hypothesis is supported by the fact that certain amounts of the pegmatitic minerals are found in pyroxenite in textural relations suggesting primary magmatic minerals. Doubtless hornblende, biotite, and feldspar in the pegmatite made way for themselves *in part* by replacement, but apparently this was a result of late magmatic action accompanying intrusion of pyroxenite rather than the effect of emanations from a younger syenitic intrusion.

The igneous rocks are cut by veins of pyrite, tetrahedrite, magnetite, specularite, chalcopyrite, gold, quartz, barite, and ankerite.

AGE AND CORRELATION OF INTRUSIVE ROCKS

Nothing new concerning the age of the intrusive rocks can be learned in Latah County. Those who have studied the Thatuna batholith agree that it should be correlated with the Idaho batholith, which, according to Ross (1928), is late Jurassic or early Cretaceous.

The relative ages of the various types of hypabyssal rocks were not determined certainly. One example of transection of lamprophyre by granite porphyry was seen. Close association of aplites and pegmatites with the batholith indicates genetic relationship. The sporadic occurrence of granodiorite porphyry and lamprophyre dikes suggests that they may differ in age from the batholith. However, the dikes do not extend far outside the area of plutonic intrusion and so probably are the same age. The possibility that some of the dikes might be early Tertiary (Anderson, 1940) or Miocene (Ross, 1934) should not be overlooked.

In view of its entirely different characteristics the Gold Hill stock may be of distinctly different age from the Thatuna batholith, as was recently suggested by Anderson (1941, p. 655).

TERTIARY EXTRUSIVE ROCKS

COLUMBIA RIVER BASALT

General statement.—The name "Columbia River basalt" is applied to Tertiary extrusive rocks in northern Idaho and bordering parts of Washington. General descriptions are given in reports of reconnaissance surveys by Russell (1901, p. 28–35), Lindgren (1904, p. 24–25), and Anderson (1930, p. 25–26). Except for brief descriptions by Johnson and Myrene (1929, p. 13) and by Goodspeed (Wilson and Goodspeed, 1934, p. 81–82) the Latah County basalts have not been studied microscopically.

Approximately 397 square miles of Latah County is underlain by lava, and most of it represents projections of the Columbia Plateau into old valleys in pre-Tertiary rocks. The top of the basalt slopes about 10 feet per mile from an elevation of 2950 or 3000 feet along the southeast margin of the county to about 2900 feet near Linden, Park, Deary, and Bovill, and to 2650 feet west of Moscow and 2575 feet west of Potlatch.

Thickness.—Near Juliaetta, Potlatch River has cut about 1700 feet below the plateau without penetrating the bottom of the lava. Of this, 250 to 350 feet represents the Latah lake beds. Possibly the maximum thickness of basalt is beneath Genesee, but it is not likely to exceed 2000 feet, including Latah sediments. The thickness of individual flows varies from a few feet to 200 feet.

Megascopic features.—The typical basalt is dark gray but weathers rusty brown. Fresh surfaces generally are lusterless and slightly rough. Usually the basalt is so fine-grained that, except for small prisms of plagioclase, minerals cannot be distinguished. Rarely the rocks are porphyritic with widely spaced phenocrysts of glassy plagioclase up to 5 mm. long.

Microscopic features.—Microscopic study of 20 specimens shows more uniformity

than indicated by hand specimens. The texture generally is intergranular to intersertal but is pilotaxitic where the rock is finer-grained and contains fewer dark minerals. The average grain varies from 1.2 mm. to 0.15 mm.

Three-quarters of the specimens contain olivine up to about 25 per cent but averaging less than 10 per cent. The other main variation is that some specimens are rich in magnetite and augite, which total 75 per cent in one case. The volumetric Rosiwal mode of a typical specimen (Pl. 5, figs. 3, 4) of olivine basalt is: 43.8 per cent labradorite, 28.6 per cent augite, 4.0 per cent magnetite, 3.4 per cent olivine, 1.8 per cent apatite, 17.3 per cent glass, 1.2 per cent chlorophaeite, and a small amount of carbonate. The rock is from the bottom of Little Potlatch Canyon in SW. $\frac{1}{4}$, SW. $\frac{1}{4}$ sec. 11, T. 38 N., R. 4 W., at an elevation of 2180 feet. Additional minerals in other specimens include titaniferous magnetite or ilmenite, iddingsite, chlorite, serpentine, limonite, and leucoxene. The average composition of labradorite in all sections is $Ab_{42}An_{58}$, which is close to Ab_3An_4 given by Calkins (1902, p. 161) for Columbia River lavas in John Day Basin.

Brown glass occurs except in rocks poor in dark minerals. It is light where free of crystallites or almost opaque where crowded with them. In the specimen reported above, the index of refraction of glass was 1.508 ± 0.004. George (1924) reported the average index of basaltic glass to be 1.575. According to his curves a glass with index 1.508 should have a composition similar to granodiorite. This result suggests the extent of magmatic differentiation when 83 per cent of the basaltic magma had crystallized.

Tuff.—Beds of tuff between or beneath basalt flows are common. The unaltered material varies from black to white. The microscope shows highly altered glass and much foreign quartz, feldspar, and mica. The most characteristic feature is alteration to pink or brick red. The alteration extends throughout the mass of tuff but does not affect basalt flows above and below. An instructive example is on Dry Creek about $1\frac{3}{4}$ miles south of the Troy-Deary highway, where a bed of tuff 23 feet thick rests on granite and is overlain by unaltered basalt. The lower 8 feet of tuff is white, while the upper 15 feet is red. Whatever the cause, the color difference must have existed before extrusion of the basalt. This point is important in connection with the origin of certain basaltic clays described later.

Age.—The age of at least part of the Columbia River basalt in Latah County is fixed by its relationship to the Latah beds which occur at more than one horizon between flows. These beds have been assigned to the middle or upper Miocene (Knowlton, 1926; Berry, 1929; Brown, 1936), but Berry (1934, p. 101) has suggested that in this area deposition may have extended into the Pliocene.

YOUNGER LAVA

General relationships.—Lava flows much different from typical Columbia River basalt occur north and south of the Thatuna Hills. The rocks underlie 32 square miles, mostly in seven areas in Palouse Valley. An eighth occurrence is on the southeast margin of the Thatuna Hills, between Randall Flat School and Troy.

Contrary to the distribution of the Columbia River basalt, the younger lavas do not rise to a constant elevation on the hills. The flows are found at elevations up to 3050 feet, while the top of the Columbia River basalt is at 2800 feet on the east and

2650 feet on the west. The lowest elevation at which younger basalt was seen is about 2500 feet near Potlatch, where the top of the youngest Columbia River flow is at 2650 feet. The younger basalt is covered with loess, and the Palouse River and tributaries have cut valleys through loess and into the basalt to depths as great as 100 feet.

Loess covers the contact between the two lavas, but the relationships indicate that the latest Columbia River flows were cut by valleys 150 feet deep before extrusion of the younger lava. The constant upper level of Columbia River basalt may indicate extrusion from distant vents to the west, while the variable upper level of the younger flows may indicate local eruptions.

Possibly the thickness at one place is no more than 100 feet. Flows probably originated at a number of vents and moved down hillsides and valleys through small distances compared with those through which individual Columbia River flows may be traced.

Cinder cone.—Kirkham (1927, p. 4, 5) and Scheid (1937) described the small cinder cone half a mile east of Princeton but did not mention its association with lavas distinct from the Columbia River basalt. The cone is several feet high, and its top is surrounded by a basalt flow. Beneath the flow for a few hundred feet laterally are tuff and scoria inclined away from the vent. The fragmental material is brown, red, and pink, but the basalt is black and shows the features typical of the younger flows. The vent is at a low elevation compared to most of the younger lava. No fragmental material was found elsewhere with the younger lava, nor have other vents been found.

Megascopic features.—Columnar jointing is not so conspicuous as in Columbia River flows, nor is it so persistent vertically. Cross joints are more closely spaced than in Columbia River lavas and divide the rock into curved plates 1 to 4 inches thick and 2 to 3 feet in diameter. There is no enlargement of joints by weathering as in the Columbia River basalt, nor do ball-and-socket joints occur.

The younger flows weather to characteristic chocolate color, but the fresh rock is black, with an almost satiny luster, brilliant when compared with a dull specimen of Columbia River basalt. Glassy phenocrysts of colorless to amber labradorite are typical. These generally are about 5 mm. long and 2 mm. in diameter and may be sparse or may compose 10 per cent of the rock. Rare phenocrysts of olivine are up to 3 mm. in diameter.

Microscopic features.—Texturally the younger lava is quite different from Columbia River basalt (Pl. 5, figs. 2–4). The younger flows are porphyritic with groundmass fine-granular to intergranular. Two sizes of plagioclase phenocrysts are about 5 mm. and up to 1 mm. in length, respectively. The former have sharp edges and corners, while the latter are ragged (Pl. 5, fig. 2). Olivine forms phenocrysts and also is in the groundmass.

Rosiwal analysis of a typical specimen from sec. 20, T. 42 N., R. 4 W., along Crane Creek, shows: 50.9 per cent plagioclase, 21.6 per cent pyroxene, 12.3 per cent magnetite, 7.7 per cent olivine, 1.5 per cent apatite, 6.0 per cent chlorite. This is not essentially different from the composition of Columbia River basalt, except that glass is typically absent. The large plagioclase phenocrysts are about $Ab_{45}An_{55}$, while

the small phenocrysts and the feldspar in the groundmass range from sodic labradorite to calcic andesine and probably average a little more sodic than $Ab_{50}An_{50}$. Pyroxene forms stubby prisms about 0.05 mm. long, frequently in clusters. Generally it is colorless but in a few specimens approaches the brown angular augite of the Columbia River basalt. Apatite crystals, frequently hairlike, are elongated up to 0.4 mm. One section contains biotite and basaltic hornblende, both much resorbed. Olivine is universal, slightly altered to chlorite. Part of the chlorite, frequently rather abundant, probably has formed from other ferromagnesian minerals. The rock should be classed as basalt rather than andesite.

Age.—Field relations indicate that in part the younger lavas filled valleys eroded in the upper flows of Columbia River basalt. Although the bulk of Columbia River basalt is middle or upper Miocene, the upper flows may be Pliocene. If so, the "younger lava" also is Pliocene or younger. It is covered by Pleistocene loess.

ORIGIN OF CLAY DEPOSITS

GENERAL STATEMENT

Clay deposits constitute Latah County's most important economic resource. Several investigators (Soper, 1918; Skeels and Wilson, 1920; Wilson, Bennett, and Heath, 1923; Hite, 1930; Tullis and Laney, 1933; Wilson and Goodspeed, 1934; Scheid, 1940a) have reported, but Plate 6 shows several deposits previously unnoticed. Because of difference of opinion, a brief summary of geologic conditions is given, together with observations additional to those in the writer's earlier report (Tullis and Laney, 1933).

There are three types of deposits: (1) residual from granitic and metamorphic rocks, (2) transported, derived from the first type, and (3) basaltic. The second type will not be discussed since its origin is clear. Goodspeed believes that the granitic clay is hydrothermal and that the basaltic clay results from weathering. Both views are opposed to those of the writer. Scheid believes that certain of the basaltic clays result from weathering.

GRANITIC CLAY

Geologic conditions.—The pre-Miocene rocks, excepting some of the fine-grained metamorphic rocks and the Permian(?) volcanics, are badly weathered in most outcrops. However, this widespread alteration is superficial when compared with changes found at places in the granitic and metamorphic rocks. Where indicated on the geologic map (Pl. 6) at a number of points along the south margin of the Thatuna batholith and about stocks to the southeast, the igneous and, at a few places, the metamorphic rocks are completely altered to clay with no remnants of original fresh minerals except quartz, muscovite, and some accessories. Feldspar and biotite are completely altered to kaolin, and the product is pure white except where overlain by basalt. One deposit underlies about a square mile, and in some cases drilling 100 feet has not revealed the bottom. There are no special channels of alteration.

Two rules govern the distribution of the residual clay: (1) It is associated with margins of basalt flows against the hills of older rocks and is found beneath the margins of the flows, or not far beyond and above. If the clay is a few miles beyond

the edge of the basalt on the uphill side, the deposits are not far above the basalt. (2) In all such places the clay is restricted to flat divides.

Wilson and Goodspeed (1934, p. 65) believe that the curved line along which the clay deposits are found "indicates the plane of contact between the granitic intrusives and the older Algonkian rocks, where the opportunities for alteration and kaolinization were greatest." This statement is to be considered in the light of Goodspeed's belief that the clay has been formed by hydrothermal solutions, in the closing stages of intrusive activity. His geologic sketch map shows the residual deposits, with one exception, located near the margins of the basalt flows, as the writer indicated above, so he must have believed that the contact between granodiorite and metamorphic rocks is buried beneath the basalt not far from its margin. All but 3 or 4 of the 14 deposits shown on Goodspeed's map are transported clays that have been moved downhill toward the supposed position of the intrusive contact, through distances in some cases probably a mile or more from the original residual deposits. The writer has found that, of the residual deposits shown by Goodspeed, Joel is near an intrusive contact and the others are from 1 to 3 miles inside the intrusion. On the south side of the Thatuna Hills the basalt overlaps onto the granitic rocks, and residual clay deposits are large and numerous, while on the north side the basalt does not overlap the granitic rocks at most places, and residual clay deposits are absent.

The relationships of the transported clays offer evidence of the time of formation of the parent residual clays. The transported clays generally occur within the area of the basaltic plateau, mostly not more than a mile from its margin, and either on top of or immediately beneath the youngest flow. The residual clays which were the source of the transported bodies must have been formed before extrusion of the basalt. At the Johansen pit a thin, unaltered flow overlies granodiorite almost completely altered to an unknown depth.

Mineralogy.—The clay preserves the texture of the original rock. Microscopic examination shows the principal new mineral to be kaolinite (Tullis and Laney, 1933). Feldspar and biotite alter to kaolinite almost completely, but muscovite alters only locally, although few flakes are entirely free of alteration as shown by marked decrease in higher indices of refraction. The largest kaolinite crystals probably come from biotite (Pl. 5, fig. 5). Micaceous minerals resembling muscovite, but with lower birefringence, and an isotropic mineral, probably halloysite, form intermediate stages. Microscopic study of samples from a vertical range in the Johansen pit indicates that biotite and muscovite flakes are fresher with depth. Accessory minerals in the clay are the same as in the original rock and seem to be present in the same amounts.

Goodspeed (Wilson and Goodspeed, 1934, p. 65, 79) reports kaolinite as the dominant mineral but also emphasizes the presence of a mineral he believes to be dickite, for which he does not give complete data. The writer has rechecked optical properties of the minerals in his own samples but has found none conforming to dickite.

Origin.—Goodspeed's belief that the clay results from hydrothermal alteration seems to be based on the following points: (1) the presence of a certain amount of dickite; (2) the occurrence of minerals such as epidote, cyanite, and tourmaline believed to have resulted from igneous metamorphism; (3) the irregular distribution

of the completely kaolinized rock; and (4) the occurrence of the deposits along a curved line believed to approximate the contact of the igneous intrusion.

If dickite is present, hydrothermal action must be considered. The optical properties of the mineral should be more completely investigated. It is agreed that kaolinite is the chief mineral. The accessory minerals attributed to hydrothermal action also are present in the unaltered rock, apparently in the same amounts as in the clay. The irregularity of clay distribution is believed by the writer to result from erosion of more extensive deposits with preservation on certain flat divides where basalt has protected the clay by maintaining a low gradient. Detailed mapping on both sides of the Thatuna Hills has shown that the exposed clay is not distributed along the intrusive contact but rather is related to the protective margin of the basaltic plateau. In addition to these answers to Goodspeed's arguments, the writer's belief that the clay deposits result from weathering is based on the following points:

(1) The clay is homogeneous over areas up to a square mile.

(2) There is no evidence of channels followed by hydrothermal solutions.

(3) The principal clay mineral is kaolinite, which is believed to be formed in abundance only by weathering (Ross and Kerr, p. 174–176).

(4) Alteration of biotite and muscovite apparently decreases at depth.

BASALTIC CLAY

At a number of places basalt has been altered to clay. Of 12 localities visited, 10 exhibit light gray color. Exposures show only cross sections, and little can be learned about areal distribution. The widths vary from 50 to 300 feet. Laterally the clay grades from soft, friable material into solid basalt. Detailed mapping shows the clays are in the top as well as in the older flows.

The clay near Troy shows genetic relationship. The best known exposure is in the NE. $\frac{1}{4}$ sec. 18, T. 39 N., R. 3 W., about half a mile below the Troy-Deary highway. The outcrop extends along the creek for 200 feet, and the clay grades sharply into unaltered basalt at both ends. The clay is wider at the bottom. It has lost all traces of basaltic jointing and is marked by solution channels. Bleaching is at a maximum at the center of the deposit. In the stream bed is an unknown thickness of altered pink tuff. The slope above the outcrop is covered with basaltic talus and stream boulders, but on the plateau, a short distance from the valley and about 300 feet above the outcrop, more clay occurs. The line between the exposures strikes about N. 50 W., and on the extension of the line in that direction are four additional clay outcrops within $1\frac{3}{4}$ miles. The two most distant are in railroad cuts and a highway cut west of Troy. Fresh basalt intervenes between clay exposures.

The late Dr. F. B. Laney believed that the clay was formed by hydrothermal action during the period of extrusive activity. The writer believed that the evidence supports this idea and gave the matter little thought until Goodspeed (Wilson and Goodspeed, 1934, p. 66–67) concluded that the clay was formed by weathering before it was covered by later flows. He suggests that lack of continuity results from younger flows filling valleys in the weathered basalt. Scheid (1940a, p. 9, 46) believes that the numerous deposits of gray clay result from weathering but agrees

(personal communication, April 22, 1941) that the deposit near Troy is of hydrothermal origin. Evidence supporting the hypothesis of hydrothermal origin is:

(1) Clay occurs not only in the older flows, as believed by Goodspeed, but also in the younger.

(2) Clay occurs in limited areas and grades laterally into fresh basalt at the same elevation. This is true both of buried and surface flows. Goodspeed's hypothesis that fresh flows filled valleys cut in weathered basalt does not explain gradational contacts or the occurrence of clay in the youngest Columbia River flows in the region.

(3) The altered clay at Troy is in a vertical range of 300 feet and appears to be localized along a vertical plane cutting more than one flow.

(4) In spite of considerable iron in the clay, it generally is gray and not red as would be expected if the deposits had been formed by surface waters carrying oxygen. In contrast, certain tuff beds are red apparently from oxidation at time of deposition or at least before extrusion of overlying flows.

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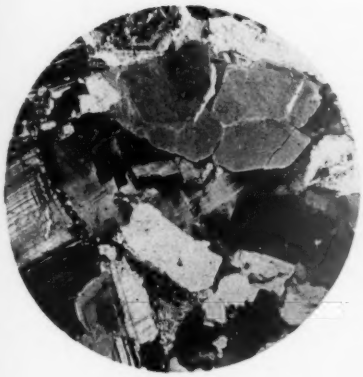
EXPLANATION OF PLATES 4 AND 5

PLATE 4.—PHOTOMICROGRAPHS OF INTRUSIVE ROCKS

Figure

1. Granodiorite. Minerals are quartz, andesine, microcline, and biotite. Microcline is the latest to crystallize and in part has formed at expense of earlier minerals. Specimen 16, Table 4. Crossed nicols, ×23.
2. Perthosite. Specimen 30, Table 4. Crossed nicols, ×23.
3. Granodiorite porphyry from Dry Creek. Phenocrysts of plagioclase, quartz, magnetite, and biotite in a groundmass of quartz, biotite, and plagioclase. Specimen 1, Table 5. Ordinary light, ×23.
4. Quartz spessartite. Minerals are labradorite, augite, chlorite, quartz, epidote, and magnetite. Specimen 5, Table 5. Ordinary light, ×23.
5. Hornblende syenite from Gold Hill. Contains microcline, microcline-microperthite, plagioclase, hornblende, augite, and sphene. Specimen 1, Table 7. Ordinary light, ×23.
6. Biotite-ilmenite pyroxenite from Gold Hill. A rim of sphene may be seen about the ilmenite. Specimen 4, Table 7. Ordinary light, ×23.



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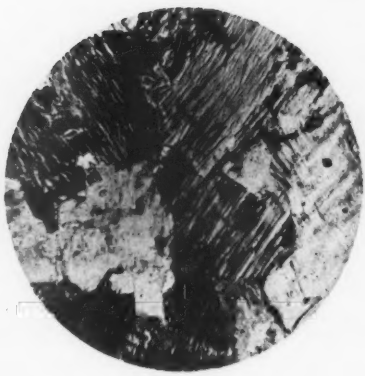

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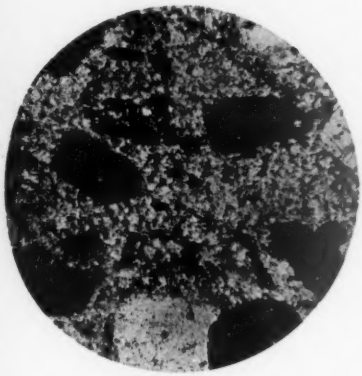
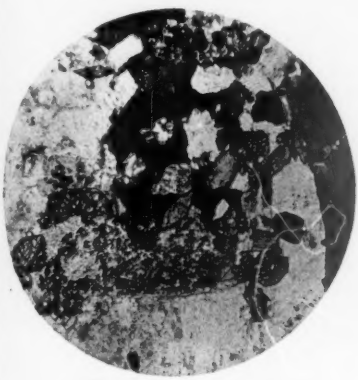


FIGURE 3

FIGURE 4



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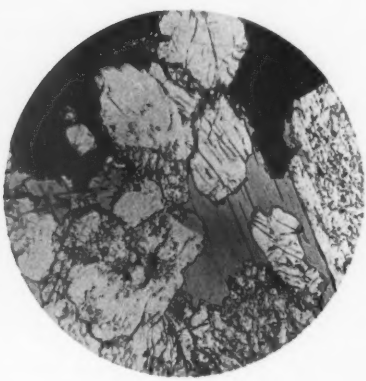
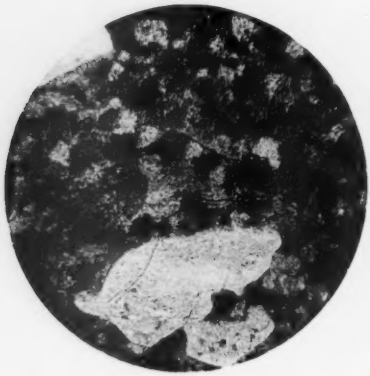


FIGURE 6

PHOTOMICROGRAPHS OF INTRUSIVE ROCKS



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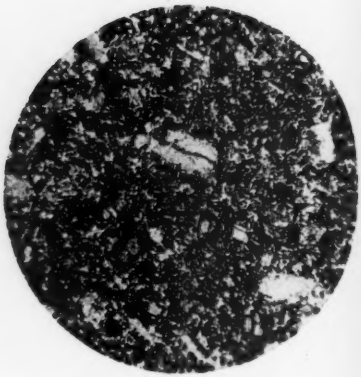

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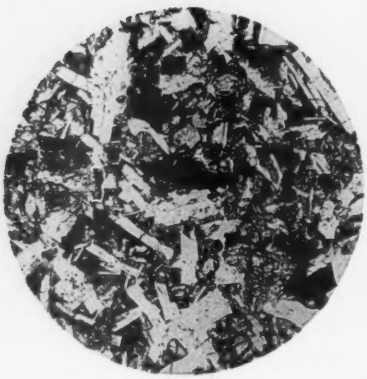

FIGURE 3

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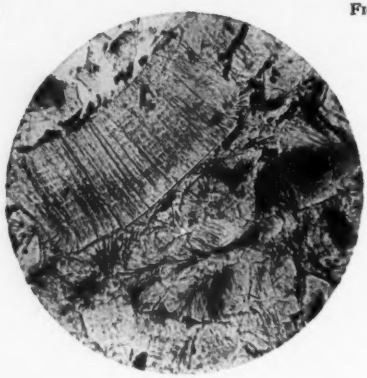


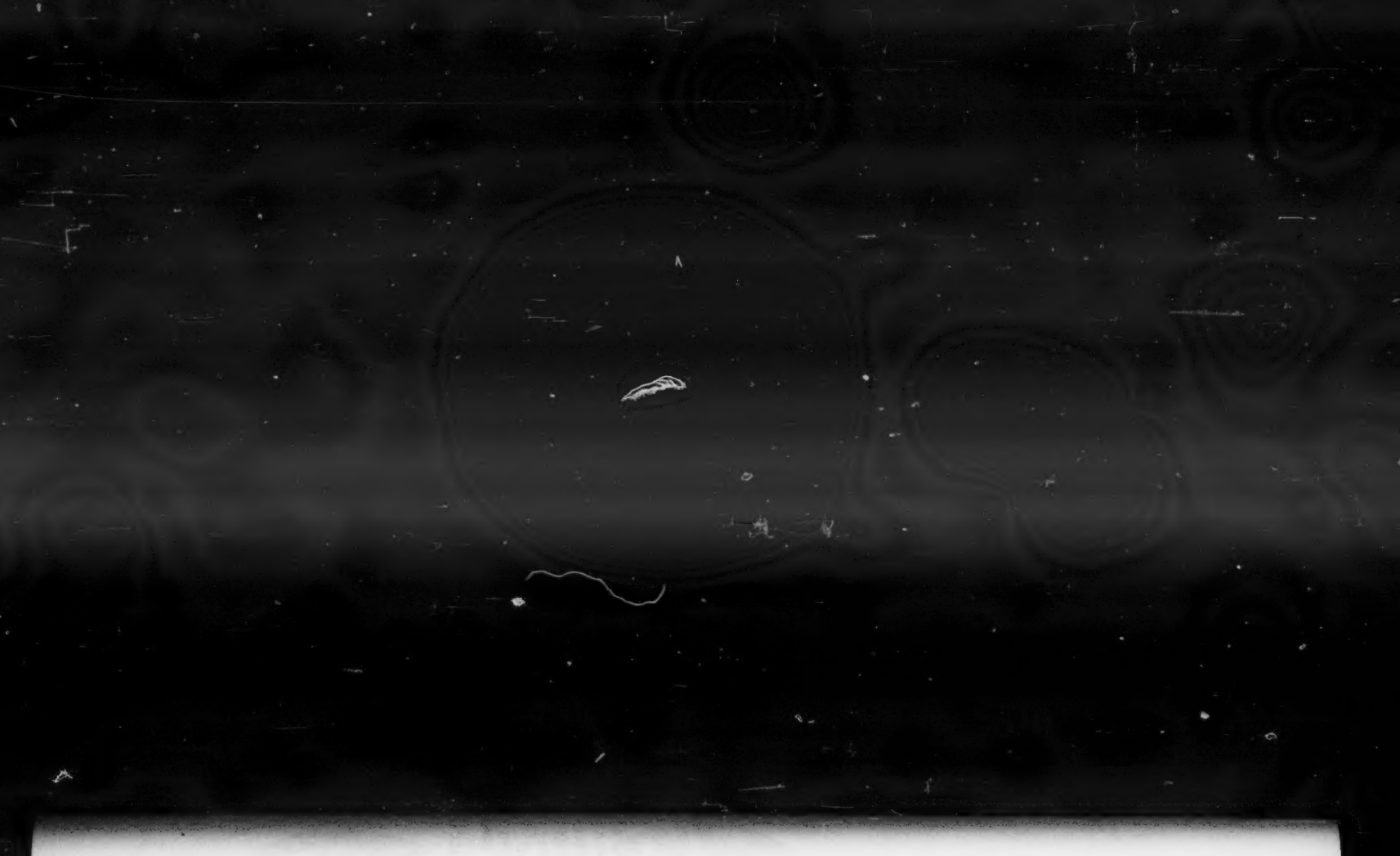
FIGURE 5

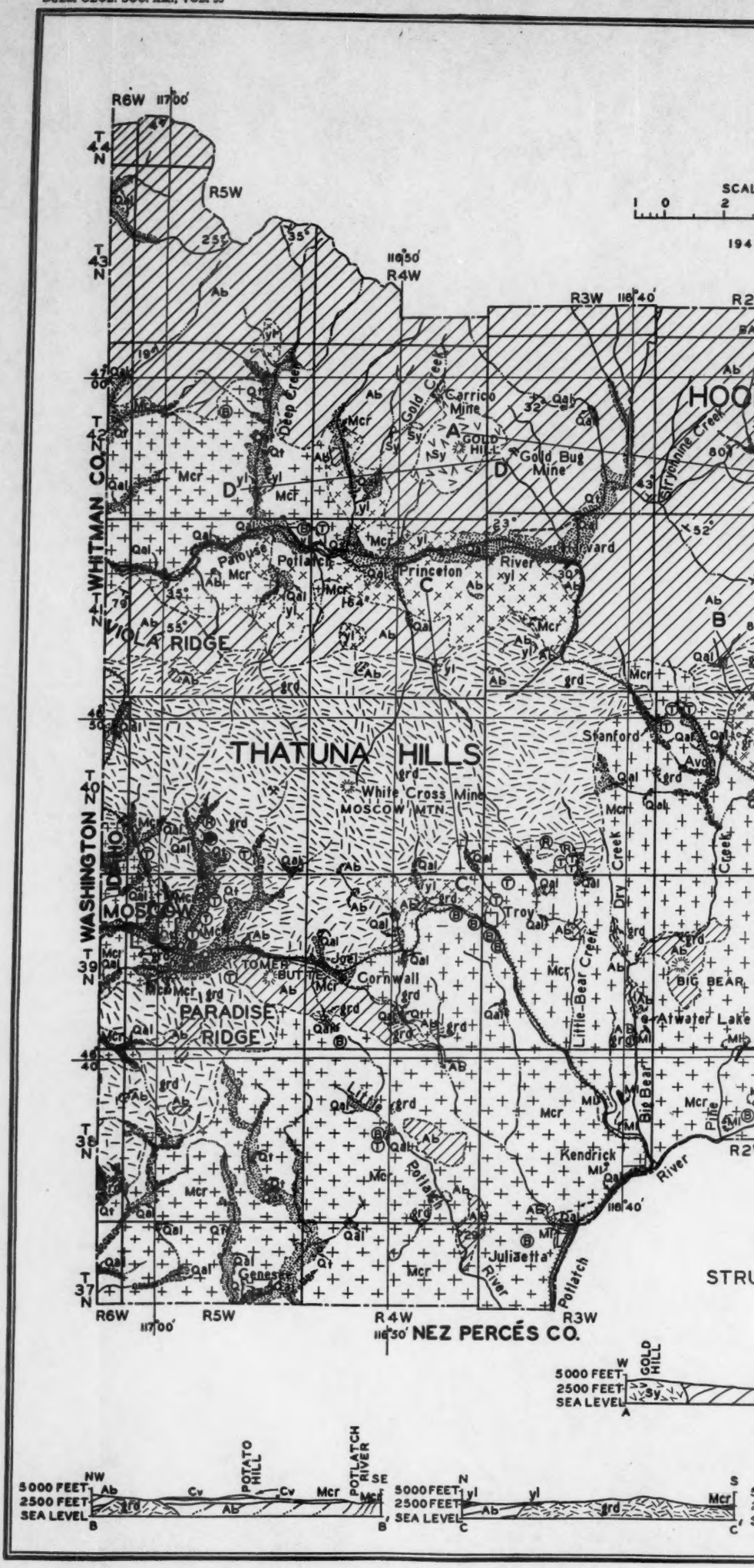
PHOTOMICROGRAPHS OF EXTRUSIVE ROCKS AND OF RESIDUAL CLAY

PLATE 5.—PHOTOMICROGRAPHS OF EXTRUSIVE ROCKS AND OF RESIDUAL CLAY

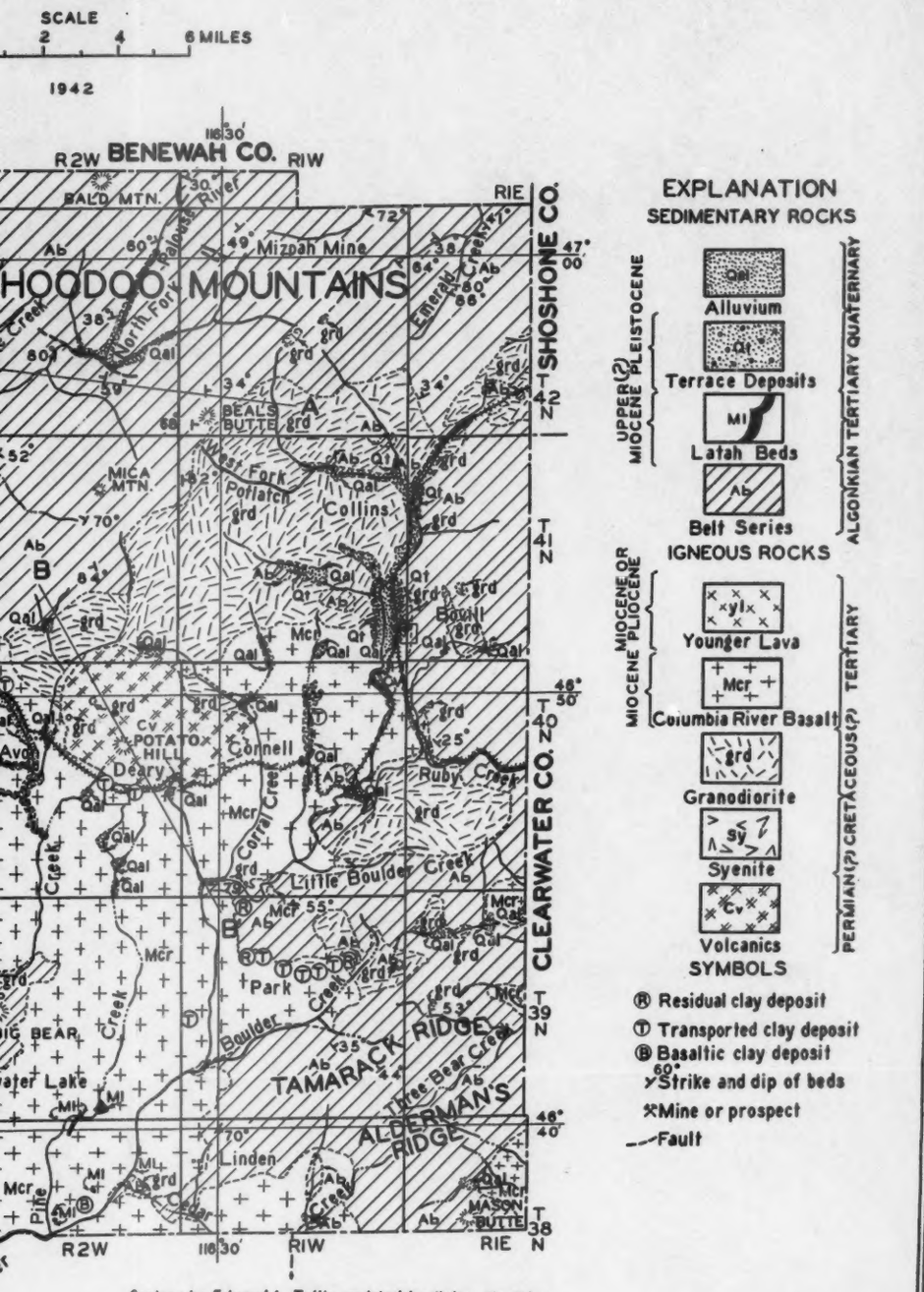
Figure

1. Dark rhyodacite from ridge northwest of Potato Hill. The mottled groundmass has micropoikilitic texture, the detail of which cannot be seen at this magnification. Note partially resorbed phenocrysts of oligoclase. Crossed nicols, ×23.
2. Younger lava from Crane Creek. Crossed nicols, ×23.
3. Columbia River basalt. Typical olivine basalt. Ordinary light, ×23.
4. Same as Figure 3, crossed nicols.
5. Kaolinite in residual granitic clay. Kaolinite is forming from biotite, dark remnants of which are visible. Lower nicol only, ×76.



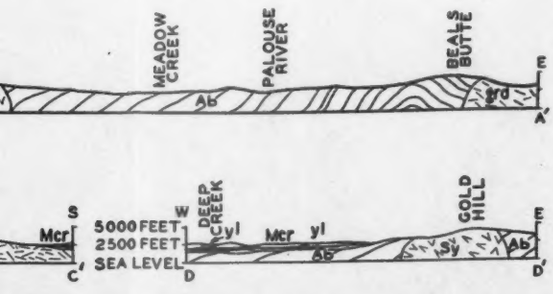


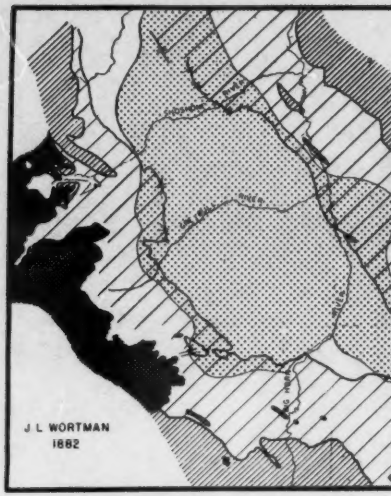
GEOLOGIC MAP OF LATAH

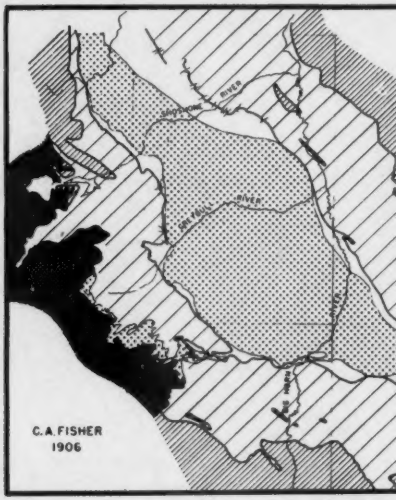


Geology by Edward L. Tullis, assisted by Walter Northby, Idaho Bureau of Mines and geology, 1931-32. Base from topographic map prepared by Walter Northby and Joe Cremans, 1931-32, and from Land Office plats. U.S. Bur. of Soils, U.S. Forest Service and U.S. Geol. Surv. maps.

STRUCTURE SECTIONS





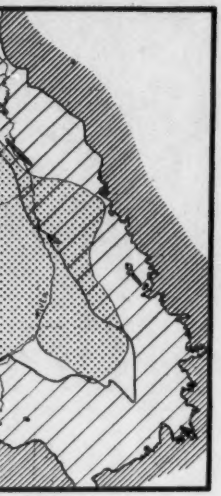


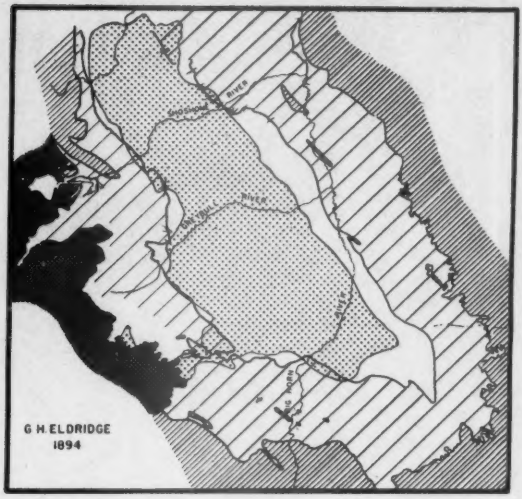
CENOZOIC

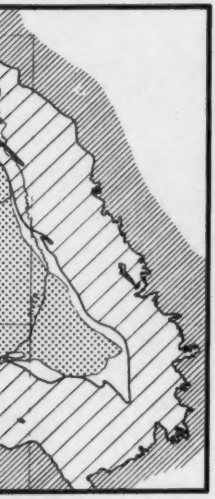
TERTIARY VOLCA

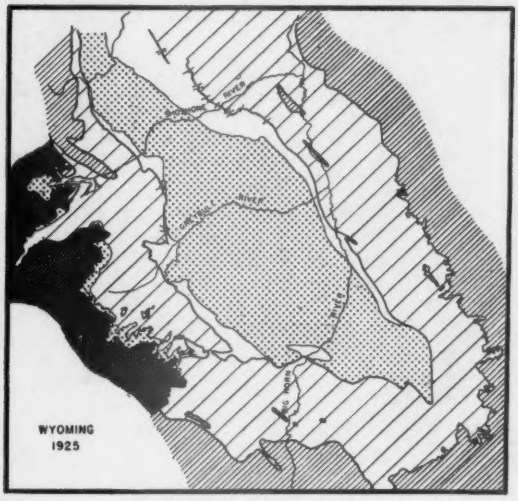
DISTRIBUTION OF THE "WASATCH"

Pre-"Wasatch" boundaries on each of these ma
the areas assigned to "Wasatch" on maps of the b









ERTIARY VOLCANICS | PALEOZOIC and PRE-CAMBRIAN | MESOZOIC | WASATCH" (=WILLWOOD)

VASATCH" (= WILLWOOD) ON EARLIER MAPS OF THE BIG HORN BASIN

of these maps are from the Geologic Map of Wyoming, 1925, to serve as a base for comparing aps of the basin.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 55, PP. 165-210, 7 PLS., 4 FIGS. FEBRUARY 1944

STRATIGRAPHY OF THE WILLWOOD AND TATMAN FORMATIONS IN NORTHWESTERN WYOMING

BY FRANKLYN B. VAN HOUTEN

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ABSTRACT

The formation name Willwood is proposed for variegated shales and hornblende-bearing sand stones conformably overlying the Polecat Bench formation near the center of the Big Horn Basin Wyoming, and truncating folds along the western margin of the area. Willwood sediments were deposited in a forested lowland, under warm-temperate conditions. Sinking of the structural basin was slower than Willwood deposition for upper Willwood deposits spread laterally beyond the lower part of the formation. Pre-Cambrian pebbles in both Polecat Bench and Willwood conglomerates indicate erosion of the pre-Cambrian cores of the uplifts surrounding the Big Horn Basin during late Paleocene and early Eocene time. Locally, the Willwood yields Clark Fork (Late Paleocene) mammals. Above the Clark Fork beds Willwood deposits contain mammals characteristic of the Early Eocene (Wasatchian).

The Tatman formation (early Bridgerian) lies conformably upon the Willwood and below the basic breccia capping Squaw Buttes. It consists of about 870 feet of alternating fine-grained sandstone and laminated brown carbonaceous shale, swamp and lake deposits which accumulated under conditions analogous to those that produced the shore facies of the Green River formation.

Late Cretaceous and early Cenozoic orogenic movements effected no pronounced change in the topography or in the climate of the Big Horn Basin.

INTRODUCTION AND ACKNOWLEDGEMENTS

In a "report of the reconnaissance made in 1873 for a wagon-road from the line of the Union Pacific Railroad in Wyoming Territory to the Yellowstone National Park and Fort Ellis, Montana Territory" Captain W. A. Jones recorded the first geological description of the Big Horn Basin region. He considered the southern Absarokas

"probably the most remarkable one of the great Rocky Mountain chain. The original range, if there ever was one, and of this there are many indications, lies buried beneath an outpouring of material from the fluid interior of the earth, which it is safe to estimate as being now from 4,000 to 5,000 feet thick.... This mountain mass has been eroded to a remarkable extent, and the streams have cut their channels into it accordingly in the most irregular manner (p. 51–52).... From our dangerous perch [the Washakie Needles] the view, spread out to the north and west, was grand and even terrible. As far as could be seen lay jagged masses of peaks of dark-brown volcanic ejectamenta, which showed black in the shadow of the falling sun, giving to the whole that appearance of black shadow and mystery which always produces such strong impressions on the mind." (p. 15)

Along the North Fork of the Shoshone River

"the mountains are very rugged. The rocks are mainly limestone, sandstone, and a coarse volcanic conglomerate. The sedimentary rocks soon disappear, and the peaks are composed of apparently horizontal layers of volcanic ejectamenta. The prevailing color is a dark reddish brown, which gives the mountains their marked black haze in shadow and bronze tint in the light. The conglomerate weathers into the most fantastic pinnacles, needles, and grotesque forms (p. 18)... The Big Horn Basin is generally barren, except the narrow belts along the streams, the foothills

of the Sierra Shoshonee [now the southern Absarokas] and Owl Creek Mountains, and the strip of country along the base of these mountains, which is tolerably well watered, fertile, and clothed with grass. Except along the streams, but little timber occurs. The general aspect of the country is rugged, parched, and barren" (p. 52).

Professor T. B. Comstock, the geologist of the expedition, supposed (1873) the red-banded Cenozoic sediments in the Big Horn Basin were Miocene lake beds.

When Cope learned that mammals had been found in the Cenozoic deposits in the basin he sent out a fossil-collecting expedition under the direction of J. L. Wortman. Examination of the many specimens discovered in 1881 revealed that the variegated strata were Early Eocene. Moreover, Cope (1882a) called the formation Wasatch because he considered it equivalent to the fossiliferous part of the Wasatch group in southwestern Wyoming and adjacent Utah. Field parties visited the basin again in 1891 and secured new mammals that enhanced the Early Eocene collection. Wortman (1882; 1892) sketched the distribution of the "Wasatch" and described its general features, though new evidence fails to confirm his claim that the sediments were deposited in a lake or that the mountains around the basin were higher in Early Eocene than now.

The geologic map accompanying Eldridge's *A geological reconnaissance in northwest Wyoming* (1894) first showed the unique border belt of folds, but no accurate map of the basin was prepared until Fisher completed a comprehensive geological investigation in 1906. His observations of the "Wasatch" sediments led him to infer a fluviatile origin, a conclusion substantiated by Loomis' analysis (1907) of the Early Eocene fauna. Loomis also noted the presence of *Lambdotherium* in the upper part of the "Wasatch" in the Big Horn Basin, indicating correlation with the Wind River formation in the Wind River Basin.

Following Fisher's important work, the United States Geological Survey examined the coal and oil resources of the region. Its reports provide detailed stratigraphic descriptions of all the formations as well as very accurate maps of the areas studied. In 1917 Hewett and Lupton published a survey of the anticlines in the southern part of the basin. Hewett later (1926) reported on the geology of the Oregon Basin, Meeteetse, and Grass Creek quadrangles, and Pierce and Andrews (1941) described the western margin of the basin south of Cody. In 1941 Pierce contributed an interpretation of the Heart Mountain and South Fork thrusts. The best map of the entire basin is part of the Geologic Map of Wyoming compiled by members of the United States Geological Survey in 1925.

The research of Sinclair and Granger from 1910 to 1914 in the Big Horn and Wind River basins was among the pioneer attempts to interpret Cenozoic environments by analyzing both the sediments and fossil mammals. From their study much of our knowledge of the Cenozoic history of the Big Horn Basin resulted. Sinclair and Granger (1912) named and briefly described the Tatman formation; Granger (1914) proposed a tentative correlation of Early Eocene faunas in the Rocky Mountain region.

In 1930 Jepsen described an exceptionally complete sequence of Paleocene sediments in the northwestern part of the basin which he subsequently named (1940) Polecat Bench formation.

The Yellowstone-Bighorn Research Association has sponsored several projects

that have contributed to the knowledge of the basin region. Mackin (1937) elucidated the erosional history of the Big Horn Basin, and Stow (1938) showed that heavy minerals can be used to correlate the basin sediments with the orogenic and volcanic activity west of the area.

The field work for the present study, subsidized in part by the Princeton Scott Fund, was begun in 1937 and continued for the next 4 summers.

The importance of describing in detail the stratigraphic relations of the early Cenozoic deposits in the Big Horn Basin was first suggested by Dr. G. L. Jepsen, to whom I am deeply indebted for his constant interest and friendly counsel. Drs. Erling Dorf, J. B. Knight, and W. T. Thom have given much helpful criticism and advice concerning many of the problems of this investigation. Drs. C. I. Alexander, W. H. Bradley, H. H. Hess, W. G. Pierce, J. T. Rouse, L. S. Russell, and M. H. Stow have also co-operated generously.

It is a pleasure to acknowledge the able assistance of Frederick L. Ferris, Jr., and S. Austin Van Houten, and to remember the friendship and hospitality of Mr. and Mrs. F. H. Churchill of Powell, Wyoming.

GEOGRAPHY OF THE BIG HORN BASIN

Within a great structural depression surrounded by ranges of the Middle Rockies the Big Horn Basin has been carved out of Cenozoic sediments by the Big Horn and Clark Fork drainage systems (Fig. 1; Pl. 7). All the enclosing mountains, except the Absarokas, are orogenic uplifts with exposed pre-Cambrian cores flanked by upturned strata. The crystalline crests of the Bighorn and Beartooth mountains, 100 miles apart and more than 10,000 feet above sea level, now stand 22,000 feet above the pre-Cambrian floor of the basin buried beneath 17,000 feet of sedimentary rocks. Between the peripheral hogback foothills and the extensive Cenozoic substratum in the middle of the basin sinuous concentric cuestas and hogbacks outline northwest-trending folds in a border belt of anticlines and synclines. There is no structural front along the eastern margin of the Absaroka Range. Instead, the basin's border is the erosional escarpment of the Absaroka volcanic plateau beneath which border belt folds are buried.

The surface of the Big Horn Basin is continuous with the Missouri Plateau through a northern opening in the mountain rim. Much of it is broad benchland tracts at 4000 to 5000 feet, cut by lateral planation during the present cycle of degradation. Above this level rise a few residual peaks and mesas. Heart Mountain, 10 miles northwest of Cody, ascends to 8113 feet (Claire, 1938, p. 109), and the high middle peak of McCulloch Peaks, 10 miles northeast of Cody, reaches 6548 feet (W. G. Pierce, personal communication). In T.48 N., R.98 W., Squaw Buttes, surmounting an area of plateau topography underlain by the Tatman formation, attain a height of 6176 feet (Claire, 1938, p. 110).

Tatman Mountain and Polecat Bench are two of the most conspicuous flat-topped remnants of old surfaces cut during excavation of the basin fill by eastward-flowing Big Horn tributaries. Polecat Bench on the Shoshone-Clark Fork Divide is 3 to 5 miles wide and about 20 miles long. Its surface preserves a part of the basin floor When the Shoshone River flowed into the Yellowstone, before capture by a Big Horn

tributary (Mackin, 1937, p. 839–841). About 6–8 miles south of the Greybull River Tatman Mountain extends 8 miles in an east-west direction. This gravel-capped mesa, a vestige of a former Greybull corrasion surface, is 5978 feet above sea level (Claire, 1938, p. 110) at its eastern end and rises westward approximately 40 feet per mile.

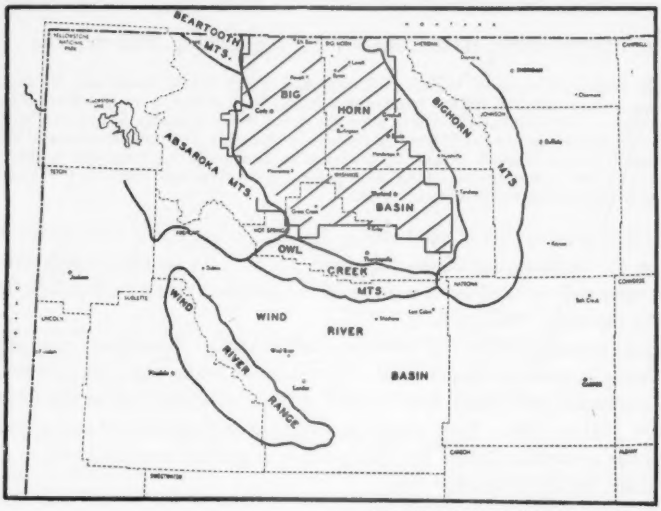


FIGURE 1.—*Map of northwestern Wyoming*

Area included in Plate 7 is shaded.

Throughout the basin there is a good deal of very rough country. Badlands have been carved in the central Cenozoic deposits wherever fine-textured drainage actively dissects steep divides and the margins of terraces and benches. The largest areas are incised on the barren slopes of McCulloch Peaks and in the wasteland between Gooseberry Creek and the Greybull River. Patches of badlands also occur locally in the deeply eroded border belt and along the Absaroka escarpment.

In the Big Horn Basin, as in the Wyoming Basin (Fenneman, 1931, p. 136–137), the superposed character of the major streams is evident. After gathering most of the waters of the Wind River Basin the Big Horn River enters the Big Horn Basin at its southern border, transecting the structural barrier in the Wind River canyon. It then flows northward near the Bighorn foothills where it is fed chiefly from the Absaroka Range by the larger Big Horn tributaries, the Greybull and Shoshone rivers, and leaves through a gorge in the Bighorn Mountains.

"It might be expected that the longitudinal stream in the aggraded Big Horn Basin should have been pressed to the eastern side . . . by waste shed from the Absaroka Mountains, no higher, but far more extensive than the Bighorn Range on the east"

(Mackin, 1937, p. 824). The predominance of drainage from the west is due not only to the greater area drained but also to the rain shadow cast by the Absarokas over the western slopes of the Bighorns.

The course of the superposed Big Horn River testifies that

> "the present drainage pattern . . . is inherited, with some modification through capture, from the pattern controlled by the slopes of the waste fill"

(Mackin, 1937, p. 824). In fact, Mackin has suggested (p. 823) that the

> "diverging Powder, Cheyenne, White, Niobrara, and North Platte rivers may be explained as radial consequents inherited from a surface of a broad fan controlled by the Wind River-North Platte system. . . . During early Tertiary time the Wind River probably joined the North Platte drainage to flow eastward to the Plains in a consequent course. The peculiar course of the present Wind River is best accounted for by capture by a headward-working tributary of the Big Horn River, at some time, before the beginning of the present cycle of erosion, when the Owl Creek Mountains were largely submerged in a sea of waste."

The northernmost part of the basin is drained by the Clark Fork which is superposed on the southern tip of the Beartooth uplift. Its course through the basin's narrow open end resulted from capture in the present cycle by a small Yellowstone tributary (Mackin, 1937, p. 853).

An arid climate (less than 10 inches rainfall annually) throughout most of the Big Horn Basin supports a desert brush vegetation of black sage, matchweed, rabbit brush, shadscale, salt brush, and a small growth of grass and weeds (Pierce and Andrews, 1941, p. 104). Only along the streams are there willows and cottonwoods. Toward the mountains where the precipitation is greater conifers grow on the hills, and grasses on the broad benches.

BIG HORN RIVER TERRACES NEAR WORLAND

GENERAL DESCRIPTION

Along the Big Horn River, in the vicinity of Worland, there is a terrace about 25 feet above the flood plain (Fig. 2). West of the river rise remnants of higher terraces cut by the Big Horn River. The third terrace is preserved as far south as Gooseberry Creek where it has been dissected; beyond the creek its extent has not been determined. A surface apparently continuous with the third terrace has been traced more than 10 miles westward along the north side of Gooseberry Creek, but a few higher remnants indicate that the extensive third terrace level west of them was not cut by the Big Horn River, for if it had been the river would have removed the residual hills.

The ascending rock steps are best displayed on a mesa on either side of Fifteen Mile Creek. Each terrace tread is about 100 feet higher, and each is mantled by 10 to 15 feet of coarse gravel (½ inch to 1 foot pebbles) composed predominantly of quartzite and chert. No limestone has been found, and igneous material is rare.

Twenty-eight miles north of the mesas the gravel of a terrace remnant dissected by Antelope Creek is both quartzite and igneous rock.

Analysis of gravels farther north (Mackin, 1937, p. 837–839, Pl. 3) shows that those of the Shoshone River and Polecat Bench and of the Greybull River and Tatman Mountain are composed almost entirely of dark volcanic rock. Igneous mate-

rial is also abundant in the Big Horn gravel near the mouths of the Shoshone and Greybull rivers. But the gravels of Shell Creek and the Big Horn River upstream from the junction of the Shoshone contain a preponderance of "Paleozoic sedimentaries" including quartzite and chert. Thus the Big Horn channel deposits are mainly chert and quartzite except where igneous rock has been introduced from the Absaroka Range by the larger eastward-flowing tributaries.

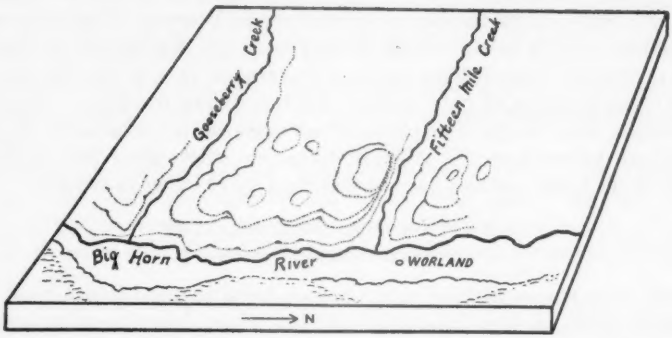


FIGURE 2.—*Sketch of the Big Horn River terraces in the vicinity of Worland*

SOURCE OF THE QUARTZITE GRAVEL

The quartzite pebbles in the Big Horn gravel probably were not eroded from the mountains south of the basin because very little quartzite has been reported there. Furthermore, the quartzite in the Big Horn gravel south of any possible source in the Owl Creek or Bridger mountains (Fanshawe, 1939, Fig. 5) could not have been derived from the mountains and deposited by the northward-flowing Big Horn River.

Hewett found abundant quartzite pebbles in the western extent of the "Fort Union" in the Big Horn Basin and delcared (1927, p. 34) that

"the quartzite resembles more than anything else on record the material that is found here and there in Algonkian sediments. The nearest general western source of this quartaite . . . lies in the Wind River and Gros Ventre mountains, about sixty miles to the southwest. Similar material may have been exposed at the surface during Fort Union time in the region west and northwest of the Wind River Mountains that is now covered with Tertiary lava flows and related igneous rocks.'

Blackwelder, who previously studied this supposed source area, had concluded (1915, p. 204) that the coarse varicolored quartzite conglomerates on both sides of the Gros Ventre Range were not derived from local rocks.

"Since there are no rocks of this character entering into the make-up of the Gros Ventre Range, these pebbles must have been imported; and the nearest appropriate outcrops are about 100 miles to the northwest."

His contention that long, powerful, eastward-flowing rivers had deposited the pebbles is cited in Love's interpretation (1939, p. 68–69) of the Aycross conglomerates of quartzite, chert, and quartz rock entirely foreign to the southern Absaroka region.

Powerful rivers may have brought early Cenozoic conglomerates from distant sources, for such deposits are lenses in several thousand feet of alluvial fill carried into

basins by aggrading streams. On the contrary, the gravel on each Big Horn terrace is the abandoned load of a degrading stream that does not seem competent to transport 12-inch cobbles from an outcrop as far removed as that suggested by Blackwelder.

Although it is not likely that the relatively small, degrading Big Horn River eroded its gravel from the basin's southern rim, nor did it carry the material from a distant source, it could have washed away finer sediments from quartzite-rich conglomerate lenses of older formations, concentrating the practically indestructible quartzite in place, or a little downstream, as a gravel veneer on each terrace. This interpretation is consistent with the geologic history of the basin. The Big Horn River was superposed on the Owl Creek-Bridger structure (Fenneman, 1931, p. 147; Mackin, 1937, p. 824) from a surface of early Cenozoic sediments filling the basin. During later degradation, when the Big Horn removed vast quantities of the basin fill, the terrace gravel was derived from the Willwood formation which, along the southwestern margin of the basin, contains quartzite cobbles 8 to 12 inches in diameter.

STRATIGRAPHIC NOMENCLATURE

PREVIOUS INTERPRETATIONS

Much of the nomenclature of early Cenozoic formations and faunas in the Rocky Mountain region has been inadequately defined; seldom have the stratal and faunal subdivisions been clearly distinguished. As a consequence the names have changed frequently in meaning and are now being used in several different senses. Among such terms, "Wasatch" has had a particularly tortuous history. Inasmuch as Nace (1936) presented an excellent summary of the literature, a complete résumé of the vagaries of "Wasatch" nomenclature is not necessary here. Only that part relevant to the Big Horn Basin is reviewed.

In 1869 the name Wasatch (Hayden, 1869, p. 161) was applied to a thick series of continental sediments near Wasatch Station, Summit County, Utah. The Wasatch group, as briefly described by Hayden, includes 1500 to 2000 feet of conglomerate exposed in Echo Canyon, Utah, and the overlying variegated sands and clays extending northward into southwestern Wyoming, so that the entire group is 3000 to 5000 feet thick. In 1871 a few mammal fossils were found in the upper part of the Wasatch group east of Evanston, Wyoming. The most common form in this small collection is *Coryphodon*, a genus previously known from deposits assigned to the Early Eocene in England and France.

During the exploration of the Rocky Mountain region by early surveys of the west, the name Wasatch was given to widely separated red-banded deposits, sometimes very distant from the type area. All were tacitly assumed to be Early Eocene because some yielded Early Eocene mammals, as had the upper part of the type Wasatch. The belief that a great "Wasatch" lake had stretched from the upper waters of the Yellowstone to New Mexico and Arizona (Cope, 1882b, p. 178) seemed to corroborate this assumption.

Because the Wind River formation was named before the Wasatch, Early Eocene deposits in the Wind River Basin have been called Wind River in most reports, although they might have been called Wasatch just as readily as the sediments of about the same age in the Big Horn and the San Juan basins. A consistent nomen-

clature would require that each isolated Early Eocene deposit has a different name, or that all such deposits, including that in the Wind River Basin, have the same name.

After the term Wasatch had gained wide usage, Veatch (1907, p. 88) showed that Hayden's Wasatch group contained three lithic units:

"(1) A basal member composed of reddish-yellow sandy clays, in many places containing pronounced conglomerate beds, which has been named the Almy formation; (2) a great thickness of light-colored rhyolitic ash beds containing intercalated lenses of white limestone with fresh-water shells and leaves—the Fowkes formation; and (3) a group of reddish-yellow sandy clays with irregular sandstone beds closely resembling (1) lithologically and separated from (1) and (2) by a pronounced period of folding and erosion. The last group has been called the Knight formation and is the horizon of the *Coryphodon* remains found in the vicinity."

Only the Knight (Table 1) could be correlated with any of the widely distributed red-banded deposits called Wasatch, for no diagnostic fossils were known from the Almy or Fowkes.

Supplementary collections from the variegated sediments yielding early Cenozoic mammals revealed distinctive faunas which Osborn (1909) called "life zones" and designated by generic names. Some of these names, however, were invalid, as in the case of the *Systemodon-Coryphodon-Eohippus* zone, necessitating frequent revision of the zone names.

"*Systemodon* Cope, 1881, has been reduced to synonymy with *Hyracotherium* Owen, 1840, and Hay in 1899 proposed *Homogalax* for the species, other than the genotype, which had been placed in *Systemodon*. *Eohippus* Marsh, 1876, is a synonym of *Hyracotherium*" (Jepsen, 1940, p. 235).

Moreover, new information has extended the range of supposed guide fossils. *Coryphodon*, for example, was thought to indicate Early Eocene age because it occurs in Early Eocene deposits in Europe; now it is known from Paleocene beds in the Big Horn Basin.

To avoid the complications resulting from Osborn's nomenclature, Sinclair and Granger (1911; 1912) applied geographic names to the faunas (Table 1), a procedure of which the United States Geological Survey disapproves (Wilmarth, 1938, p. 861). The authors defined the Lysite and Lost Cabin formations by their faunas rather than their lithic features: "For the *Lambdotherium* zone which has hitherto been synonymous with Wind River, we propose the formation name Lost Cabin."

The largest mammalian fauna found in deposits named Wasatch had been recovered from the lower part of the "Wasatch" (Cope, 1882a) in the Big Horn Basin, and this came to be regarded as the characteristic Wasatch fauna. When Sinclair and Granger recognized Lost Cabin fossils in the upper part of the "Wasatch" they described the "Big Horn Wind River" as conformably overlying the "Big Horn Wasatch", asserting (1911, p. 109) that "were it not for the presence of *Lambdotherium* and *Heptodon*, it would be impossible to differentiate the Wind River from the Wasatch either lithologically or stratigraphically." Thus the fossiliferous lower part of Cope's Wasatch became the "Big Horn Wasatch". But in 1912 Sinclair and Granger substituted the name Knight for "Big Horn Wasatch" because the Knight formation of the Wasatch group contains an Early Eocene fauna in the type locality. It followed that the Knight must be older than the "Big Horn Wind River" which yields Lysite and Lost Cabin mammals. However, when the Knight fauna was studied more carefully Sinclair and Granger did not find this. Instead, the Knight was discovered to be similar to the Lysite, whereupon a new name, Gray Bull beds

(Granger, 1914, p. 203) ,was proposed for "this most important Lower Eocene faunal horizon" in the Big Horn Basin. "The anomalous situation thus arose that the known fauna of the type Wasatch is later than the accepted 'Wasatch' fauna, and that the latter does not occur in the Wasatch Basin" (Simpson, 1933, p. 114). The term Wasatch was subsequently used by Granger for beds containing *Hyracotherium* and associated mammals. Accepting this usage, Hewett (1926, p. 91) stated that

TABLE 1.—*Names of the early Cenozoic faunas involved in the problem of "Wasatch" terminology*
Correlation was first proposed by Granger (1914)

Epoch	San Juan Basin New Mexico-Colorado	Southwestern Wyoming	Wind River Basin Wyoming	Big Horn Basin Wyoming
Early Eocene	.....Largo..... .... Almagre	.....Knight.....	...Lost Cabin... .....Lysite.....	... Lost Cabin ... . Lysite ....Gray Bull....
Late Paleocene	..... Tiffany			... Clark Fork ...

"in general the recognition of Wasatch beds is based upon the identification of characteristic vertebrate fossils," and Wegemann (1917) assigned a thick coal-bearing series in the Powder River Basin, Wyoming, to the Wasatch on faunal evidence alone. Meanwhile, Osborn (1929) continued to use "Big Horn Wasatch" for the red-banded sequence and designated the faunal units within it, from Clark Fork to Lost Cabin, A to E. Each represented a "life zone" to which Sinclair and Granger has applied a geographic name.

Fossils collected from the lower part of the Canyon Largo (replaces Wasatch; *see* Wood *et al.*, 1941, p. 16) formation in southern Colorado proved to be more primitive than the Early Eocene faunas hitherto found in strata called Wasatch. Inasmuch as the fossiliferous deposits, named Tiffany beds (Granger, 1917, p. 829–830), are part of a stratigraphic unit referred to the Wasatch they were at first placed at the base of the Lower Eocene, though Granger later concluded that they are Paleocene. In the northern part of the Big Horn Basin the late Paleocene Clark Fork fauna (also originally considered Early Eocene) occurs in variegated deposits, conformable beneath Gray Bull beds (Jepsen, 1930b, p. 493), and in central Utah Spieker (1936) found dinosaurs in sedimentary rocks assigned to the Wasatch.

CONCLUSIONS

Dunbar has observed (1940, p. 276) that one school of stratigraphers dealing with the problem of the Pennsylvanian-Permian boundary line regards "classification, even in its larger brackets, as essentially artificial. To adherents of this school any boundary is satisfactory if it is generally accepted." From this point of view, Wasatch, despite its ambiguity, should be retained for all deposits so named and mapped, and it might just as logically be applied to variegated Early Eocene sediments anywhere in the United States.

But stratigraphic nomenclature should reveal the nature of the geologic record as

accurately as possible, even if stratal and faunal subdivisions are for the most part arbitrary. The term Wasatch is not applicable to all red-banded rocks in the Cordilleran region because they did not all accumulate at the same time. Variegated sediments were deposited in the late Cretaceous and in the late Paleocene. Within the Wasatch group itself conditions causing this distinctive deposit were repeated to produce the Almy and the Knight which are separated by the Fowkes or by a nonconformity. Even those "Wasatch" strata of Early Eocene age were not everywhere synchronous. Taking cognizance of the important additions to our knowledge since the name Wasatch was first extended from the type area, the reasons for changing the name in the Big Horn Basin are compelling. It is now known that the red-banded sediments there differ from the type Wasatch in three significant respects: (1) In the type area the Wasatch group comprises three formations separated by unconformities. In the Big Horn Basin the beds called Wasatch compose a single unit of sediments. (2) Lysite and possibly Lost Cabin mammals have been found in the Knight formation of the type Wasatch (Wood *et al.*, 1941, p. 23, Pl. 1), whereas the lithic unit in the Big Horn Basin ranges from Clark Fork to Lost Cabin. (3) Undoubtedly, the basin in which the type Wasatch accumulated was isolated from the Big Horn Basin, and the early Cenozoic sediments in each basin was deposited independently.

Some geologists, conceding that the unrestricted use of Wasatch is obselete, have employed Big Horn Wasatch or Big Horn Basin Wasatch; but this falsely alludes to a closer relationship between the Big Horn Basin deposits and the type Wasatch than between the latter and the Wind River formation.

Still others, who believe further reference of the Big Horn Basin sediments to Wasatch is ambiguous and confusing, maintain that the terms proposed by Sinclair and Granger should be used in a formational sense. However, the Gray Bull, the Lysite, and the Lost Cabin have not been defined on any lithologic basis, and "a unit distinguished from the enclosing rocks only by its fossils shall not, in general, constitute a formation" (Ashley *et al.*, 1933, p. 431, Article 5c). It is fallacious, therefore, to imply by the use of "formation" or "member" that these faunas are coextensive with lithic units. There are numerous examples of formations that can be identified by their fossils alone. The contact between the Bighorn dolomite and the Madison limestone is, in some places, impossible to locate except by fossils. Nevertheless, the faunas evidence a significant hiatus. On the contrary, the mammals of these proposed formations in the Big Horn Basin reveal a closely related sequence of strata. Quite apart from any theoretical aspect of the question, the red-banded sedimentary unit should be named for purpose of reference in the absence of diagnostic mammals which are scarce except in limited areas.

The superposition of the Big Horn River across the structural barrier between the Wind River and Big Horn basins is evidence that early Cenozoic sediments once covered the mountains. If Early Eocene deposits covered the divide that portion in the Big Horn Basin should be called Wind River formation to indicate its former connection with Wind River deposits in the Wind River Basin. However, at present, no direct connection between the Early Eocene sediments in the basins makes this procedure necessary. The remnant of Cenozoic strata suggesting most strongly an inter-basin correlation is Lysite Mountain on the eastern end of Bridger Mountain.

Love believes (1939, p. 84) that the lower beds are part of the Tepee Trail formation and the upper beds are like the White River and Wiggins, while Wood claims (1940, p. 142) that Lysite Mountain is composed of sediments identical with the Green Cove (Bridgerian) and Uintan of the Wind River Basin. These correlations point to burial after Early Eocene time.

To give the red-banded formation in the Big Horn Basin a new name, indicating within it the presence of distinct faunas, would most clearly express the nature of the sedimentary and fossil record and would also differentiate these variegated beds from other deposits in the Rocky Mountain region which they resemble only because of similar mode of origin. This is no unique procedure, for recent studies of early Cenozoic sediments demonstrate that a more precise geologic interpretation is possible with the use of new formational names than is permitted by the continued misuse of older stratigraphic terms. Love (1939, p. 58) gave the name Indian Meadows to Early Eocene sediments in the Wind River Basin which are unconformably overlain by the Wind River formation. These beds had been called Wasatch, but Love considered the term too ambiguous to be retained. Jepsen (1940, p. 231) concluded that "Fort Union" is "more confusing than informative" when extended to the Paleocene deposits in the vicinity of Polecat Bench, in the northern part of the Big Horn Basin and consequently proposed Polecat Bench formation in place of "Fort Union". The so-called Wasatch in central Utah that yields late Cretaceous and Paleocene fossils has been named North Horn formation by Spieker (Wood *et al.*, 1941, p. 26), and the red-banded sediments in western Colorado, previously referred to the Wasatch, have been called the DeBeque formation by Patterson (Wood *et al.*, 1941, p. 18). Therefore, Willwood formation is here proposed for the red-banded strata in the Big Horn Basin that in their normal position overlie the Polecat Bench, or "Fort Union", formation and underlie the Tatman. The name is derived from the Willwood Division of the Shoshone Reclamation project in Park County, located between the Shoshone River and the northeastern slope of McCulloch Peaks.

NOMENCLATURE OF THE FAUNAS

Early Cenozoic mammalian faunas are seldom coextensive with the lithic units in which they occur; a fauna may be found in one or more formations, or it may be restricted to a level within a formation. Hence it is important to distinguish between faunal and stratal subdivisions except where coincidence can be demonstrated.

The standard practice in marine stratigraphy in such a situation dictates defining zones, or faunizones (*see* Arkell, 1933, p. 23), and designating each by the generic name of an abundant and characteristic fossil—a system that is effectual if beds of the same age, containing different faunal facies, can be accurately correlated. But when applied to continental Cenozoic deposits it is a confusing procedure because the equivalence of mammalian assemblages is difficult to establish. In contrast to marine environments, terrestrial realms are inhabited by a prodigious variety of animal life adapted to the diverse physical conditions prevailing on land. And yet only a few animals that lived in any particular habitat are preserved; in fact many of the faunal facies are never represented at all in Cenozoic collections. The rarity and erratic distribution of mammalian fossils vitiate their utility in delimiting rock units; they

can be used only to indicate relative ages from site to site (Jepsen, 1940, p. 227–235; Stirton, 1936, p. 164–166). Moreover, Jepsen (p. 235) and Wood *et al.* (1941, p. 7) have recounted the practical difficulties in applying the zoning system to continental Cenozoic rocks, owing to the present incomplete knowledge of the stratigraphic ranges of the genera and the "vicissitudes of zoological nomenclature".

Locality numbers or letters have sometimes been used to designate faunas, but a characterless array of numbers (or letters) will plainly lead to considerable duplication and frequent mistakes.

Geographic names have, therefore, been given to distinct fossil assemblages, or "faunas", from different stratigraphic levels or different localities. When the collection is small and from a very limited area the term local fauna is perhaps preferable. The practice of using geographic names for faunas is not sanctioned by the United States Geological Survey, yet this institution does accept as valid the Puerco and Torrejon formations which are distinguishable by fossil content alone and can be mapped only as the Nacimiento group. "Owing to the great similarity in lithology and the restriction of the fossils to relatively narrow zones with a barren interval between, no break has been recognized in the field in the series of beds, even at the localities where both formations are known to be present" (Reeside, 1924, p. 35). The fact that the occurrence of the Puerco and Torrejon fossils in the field and an analysis of the assemblages suggest a hiatus between them is cited as reason for calling the fossiliferous beds formations and using geographic names when referring to the faunas. No lithologic formations have been recognized here, but the need to refer to the faunas simply and clearly has led to the use of Puerco and Torrejon. Nevertheless, the Tiffany and Almagre are declared invalid (Wilmarth, 1938, p. 36, 2147) even though these faunas, too, are separated by a hiatus. In each case, the distinct faunas are the significant data. The use of geographic names is the most lucid and convenient way to designate them, especially when they have no precise equivalents elsewhere.

Faunas given geographic names are sometimes called members (Moore, 1936, p. 24). Such usage, however, confuses the distinction between faunas and formational units, inasmuch as a member has been defined (Ashley *et al.*, 1933, p. 438) as a lithic subdivision of a formation. That the Lysite and Lost Cabin in the Wind River Basin were called members by Wood *et al.* (1941, p. 7) in accordance with this definition is implied by reference to their sedimentary features. But the Gray Bull and Clark Fork were also called members (p. 20–21), even though they can now be differentiated only by their fossil content.

When a fauna does not coincide with an easily recognizable lithic unit, the deposits containing the fossils can be called "beds", a term that has the advantage of not being part of the formal stratigraphic nomenclature. Because geographic names are applied to these beds for convenience of reference only, they do not conflict with the names of valid stratigraphic units. Thus "Gray Bull", as originally proposed by Granger (1914, p. 203), need not be changed to "Greybull", a more recent spelling. In fact, the older spelling is best retained, since "Greybull" was subsequently applied to a sandstone member of the Cloverly formation (Wilmarth, 1938, p. 878).

WILLWOOD FORMATION

GENERAL STATEMENT

In the central part of the Big Horn Basin the Willwood formation consists of about 2500 feet of variegated shale, numerous beds of white and yellow sandstone composed of unsorted grains, and locally abundant conglomerate lenses. Occasionally the channel sands are arkosic, though usually the feldspar is decomposed. In shale layers small, irregular, rust-colored calcareous concretions abound. A mineralogical analysis of Willwood sediments reveals (Table 3; *see also* Stow, 1938, p. 757–758) an "extreme persistence and abundance of minerals derived from a crystalline rock and a scarcity of those derived from a sedimentary rock." Kyanite, which first appears in upper Polecat Bench deposits, is common in the lower Willwood but rare in the upper part of the formation. The presence of hornblende in Willwood sandstone, and its absence from the Polecat Bench and Lance, suggests that the Early Acid Breccia was the source of some of the Willwood sediments.

The oldest Willwood deposits yield mammals of the Clark Fork fauna, and the youngest, Lost Cabin mammals.

In the middle of the basin nearly horizontal Willwood strata are conformable on the Polecat Bench, a part of an essentially continuous sequence of sediments that began to accumulate in late Cretaceous time. Near the basin's margin, however, the Willwood dips basinward and is locally nonconformable or overlaps the Polecat Bench and lies on the Lance.

Wherever the Willwood and Polecat Bench are conformable no conspicuous lithologic change marks the beginning of Willwood deposition, except red banding, whose origin, then, must have been independent of conditions controlling the grain size.

Plate 1 is a comparison of the distribution of the "Wasatch" (= Willwood) formation on earlier maps. Some of the differences undoubtedly are due to inaccurate determination of locations, but most of the changes are the result of more careful study of the strata, for, although the general characteristics of the Willwood are quite distinctive, variation in its lithic features and the absence of an easily recognized basal unconformity make its delimitation difficult.

Jepsen (1940, p. 232) proposed Polecat Bench formation for the Paleocene deposits in the northern part of the Big Horn Basin that had been called Fort Union. Because his study did not include that region south of the Shoshone River, "Fort Union" will be used in this discussion for those beds in the southern part of the basin that have been mapped or described as Fort Union.

DETAILED DESCRIPTION

The distribution of the Willwood formation shown on Plate 7 is based on the literature and on maps of the Big Horn Basin region, supplemented by detailed study in critical areas. The numbered localities on this map are discussed in the following paragraphs.

(1) Eastward-dipping sediments along the Beartooth Mountain front were mapped as Fort Union by Hughes (1937, Table 1, Fig. 1) who recorded their thickness as 4300 to 6000 feet. Although extensive "Quaternary" alluvium in the vicinity of the Clark Fork makes it difficult to trace the strata to outcrops of their more typical

FIGURE 1. NONCONFORMITY BETWEEN WILLWOOD FORMATION AND CRETACEOUS SEDIMENTS
Sec. 31–33, T. 55 N., R. 102 W., looking northward.

FIGURE 2. CONTACT BETWEEN WILLWOOD AND POLECAT BENCH FORMATIONS
Sec. 12, T. 53 N., R. 101 W. Willwood strata are east (left) of valley. Looking southeastward.

FIGURE 3. POLECAT BENCH—WILLWOOD CONTACT
On southwest slope of McCulloch Peaks, secs. 17 and 18, T. 53 N., R. 100 W., looking northward. CF-Clark Fork beds in Polecat Bench formation; GB-Gray Bull beds in Willwood formation.

CONTACT BETWEEN WILLWOOD STRATA AND OLDER FORMATIONS

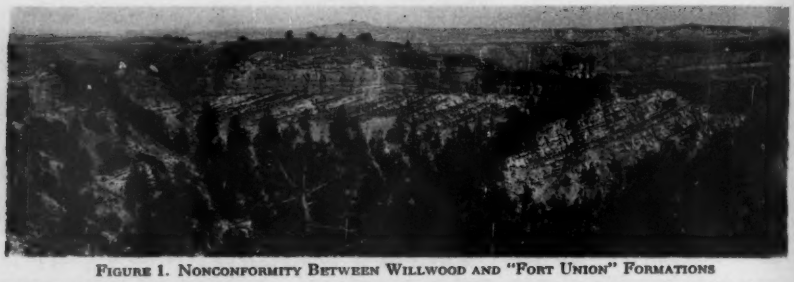


FIGURE 1. NONCONFORMITY BETWEEN WILLWOOD AND "FORT UNION" FORMATIONS
At head of Fifteen Mile Creek, sec. 7, T. 48 N., R. 99 W., looking southeastward. Squaw Buttes in distance.

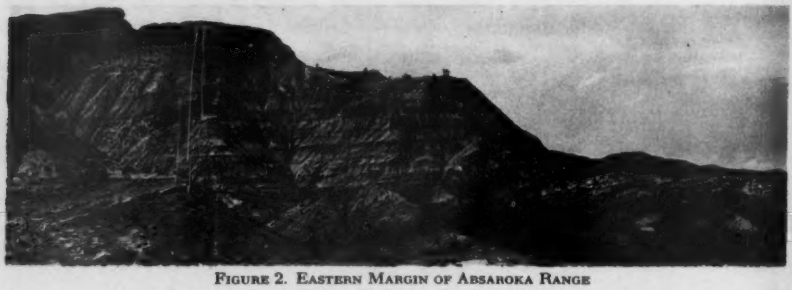


FIGURE 2. EASTERN MARGIN OF ABSAROKA RANGE
Sec. 10, T. 44 N., R. 99 W., looking northward. Red-banded Willwood beds in escarpment are nonconformable on westward-dipping Meeteetse strata. About 10 feet of Tatman beds separates Willwood and dark Early Basic Breccia at top of cliff.

FIGURE 3. "FORT UNION"—WILLWOOD CONTACT
On the south bank of Antelope Creek, on line between secs. 29 and 32, T. 51 N., R. 39 W. Coal mine at extreme left is in "Fort Union." Dip decreases gradually from east to west.

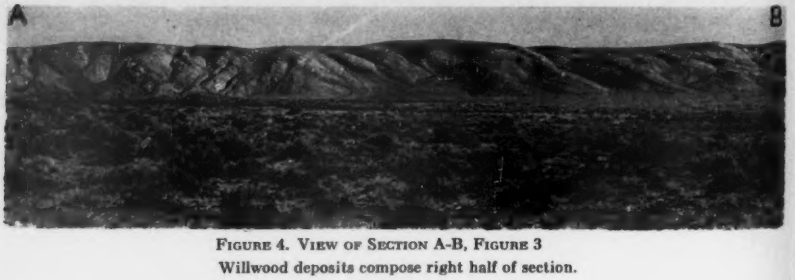


FIGURE 4. VIEW OF SECTION A-B, FIGURE 3
Willwood deposits compose right half of section.

CONTACT BETWEEN WILLWOOD STRATA AND OLDER FORMATIONS

equivalents to the southeast, the deposits have been identified by their heavy minerals (Stow, 1938, Pl. 2) as "Wasatch" (= Willwood), confirming the conclusion (Geological Map of Wyoming, 1925) based on stratigraphy. If correctly correlated, the Willwood strata cover the Polecat Bench formation and part of the Lance. The deposits consist mainly of layers of poorly sorted sandstone cut by numerous conspicuous conglomerate lenses. Bright red beds are absent. In the valley of Line Creek the dull red color is due, in part, to unaltered pink granite fragments.

Coarse Willwood sediments overlying several thousand feet of Polecat Bench sandstone, shale, and coal beds near Red Lodge, Montana, probably resulted from pronounced movement along the Beartooth thrust fault. Yet even before this deformation the Beartooth Mountains had been uplifted and their pre-Cambrian core exposed, for most of the heavy minerals in the upper part of the Polecat Bench were derived from crystalline rocks.

(2) On the divide between Pat O'Hara and Paint creeks Willwood deposits that yield a Gray Bull fauna (Jepsen, 1930a, p. 122) are composed of gray, dark-red, and lavender sandy shale and sandstone. These Gray Bull beds lie nonconformably on Cretaceous rocks (Stow, 1938, Pl. 2).

(3) About 3 miles northwest of Heart Mountain, in secs. 31–33, T.55 N., R.102 W., there is an excellent exposure of an angular unconformity (Pl. 2, fig. 1) between variegated Willwood deposits and the Lance (Stow, 1938, Pl. 2). The Willwood strata dip gently basinward, whereas the Cretaceous beds dip as steeply as 60°NE.

(4) Red-banded deposits beneath the limestone block on Heart Mountain are 7500 feet above sea level. These are the highest Willwood beds in the basin, yet only Gray Bull fossils have been found here. Near the middle of the basin Gray Bull beds are at 5500 feet on Tatman Mountain. Presumably, then, Willwood strata along the northwest side of the basin have been differentially elevated about 2000 feet.

(5) In the southeast corner of T.56 N., R.102 W., gray shale and fine-grained sandstone of the Willwood resemble Polecat Bench sediments in this vicinity. Only a few dull-red and buff layers are present. These somber Willwood beds can be traced laterally into more typical red-banded deposits. The gastropod genera *Goniobasis*, *Gonyodiscus*, *Grangerella*, *Helicina*, *Oreohelix*, and *Vivaparus*, abundant in this locality, are mostly terrestrial forms (Russell *in* Jepsen, 1930b, p. 495). *Celtis* seeds are common. The mammals discovered here are *Diacodexis*, *Didymictis*, *Haplomylus*, *Hyopsodus*, *Paramys*, and *Pelycodus*. *Coryphodon* remains are rare.

(6) Fossil mammals collected from the surface of another area of drab Willwood deposits east of Heart Mountain, in sec. 21 and 22, T.54 N., R.101 W., include *Diacodexis*, *Didymictis*, *Homogalax*, *Hyopsodus*, *Hyracotherium*, *Phenacodus*, and *Paramys*. Fish vertebrae, gastropods, and *Celtis* seeds were also found. A "quarry" in fine-grained sandy shale yielded *Diacodon*, *Nyctitherium*, *Peratherium*, *Plagiomene*, a multituberculate, and a lizard.

The few small mammal "quarries" discovered in the Willwood formation are in gray shale layers. Apparently only in this kind of deposit were mammals buried in sufficient number and preserved well enough to produce rich "pockets" of fossils. Although some of the "quarry" rock is fine-grained sandstone, there undoubtedly

was but little current action in the water bodies at the place of deposition, for any turbulence would have stirred up the sediments and damaged the delicate skulls and jaws.

(7) Lance, Polecat Bench, and Willwood strata with gradually decreasing eastward dip crop out in normal sequence in the Shoshone River section. There is an apparent nonconformity between the Willwood and Polecat Bench formations in the southern part of sec. 12, T.53 N., R.101 W. (Pl. 2, fig. 2). However, this probably is an illusion for the winding Shoshone canyon is cut normal to the strike of the Polecat Bench beds but transects the Willwood strike obliquely. The Polecat Bench deposits consist of drab shale and sandstone, and conglomerate lenses with pebbles up to 5 inches in diameter (Hewett, 1914, p. 105). A few dull-red bands are present near the top of the formation. The lowest Willwood beds are like the Polecat Bench except that there are no conglomerates. Higher in the section to the east, where red and buff layers are more abundant, Gray Bull fossils have been found.

. (8) In secs. 17 and 18, T.53 N., R.100 W., about 1½ miles east of the Shoshone River gorge, red-banded Willwood strata can readily be distinguished from the somber Polecat Bench, but the contact is not well exposed. Steeper-dipping Polecat Bench beds that are farther west than the only part of the Willwood with which they can be compared (Pl. 2, fig. 3) do not necessarily indicate a nonconformable contact (*see* Sinclair and Granger, 1912, Pl. V, p. 59) because the dip of all beds in this area increases marginward.

An incisor of a rodent found in Polecat Bench beds that yield Clark Fork mammals (Sinclair and Granger, 1912, p. 59–60; Granger, 1914, p. 203–204) is the first rodent remains to be reported from the Clark Fork fauna and the second from Paleocene deposits in North America. (*See* Jepsen, 1937.)

(9) The section of the Willwood cut by the Shoshone River reveals that the McCulloch Peaks area is a broad syncline with local flexures modifying the basinward dip of the strata. Here the structural axis of the Big Horn Basin, as in the vicinity of Squaw Buttes, lies somewhat west of the middle of the basin.

On the north slope of McCulloch Peaks the lower 400 feet of the Willwood formation is buff and gray shale with occasional carbonaceous layers. Some of the buff color of the badlands is due to weathering of the gray shale. In the upper part of the formation sandstone channel deposits and bright red shale are common, and there are many small calcareous concretions that were probably derived from the limestone blocks on McCulloch Peaks through ground-water activity.

Weathered blocks of Madison limestone and cobbles of Amsden limestone lie on the flat summits of the middle and east peaks. No Paleozoic rock is preserved on the jagged west peak, but there is a remnant of crumbled limestone on a low hill between the west peak and the Shoshone River. Rouse (1937, p. 1294) discovered a small patch of loose, angular volcanic fragments on the middle peak suggesting a former extension of the Absaroka volcanic series.

The uppermost 150 feet of McCulloch Peaks is considered to be Lost Cabin beds (Wood *et al.*, 1941, p. 25), yet Gray Bull mammals have been found within 150 or 200 feet of the top of the west peak. This leaves but a few feet for Lysite beds, if they are present here.

FIGURE 1. NORMAL FAULT IN WILLWOOD STRATA

On north flank of Tatman Mountain, T. 50 N., R. 97 W., looking eastward.

FIGURE 2. LENS OF CHANNEL SAND IN WILLWOOD FORMATION

In T. 47 N., R. 96 W. At left edge of lens sandstone dike transects overlying red shale.

FIGURE 3. LENSES OF COARSE CONGLOMERATE IN WILLWOOD FORMATION

North of Gooseberry Creek, in SW. ¼ T. 47 N., R. 98 W.

FIGURE 1. SQUAW BUTTES

On divide between Fifteen Mile and Gooseberry creeks, looking northward. Substratum of plateau is Tatman formation. Tatman Mountain forms distant skyline.

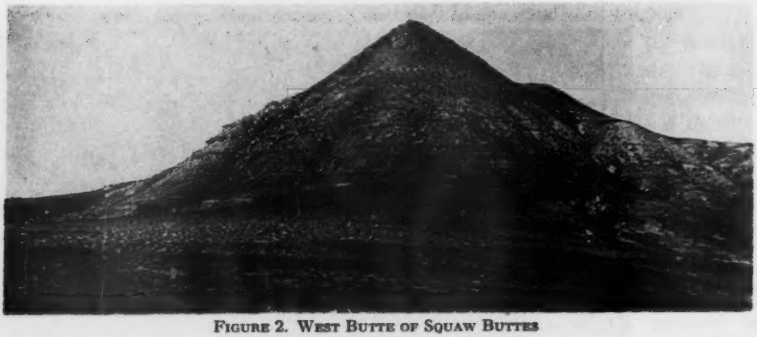


FIGURE 2. WEST BUTTE OF SQUAW BUTTES

Upper fourth is Early Basic Breccia.

FIGURE 3. ANGULAR BRECCIA FRAGMENTS AT SUMMIT OF WEST BUTTE

(10) On the east flank of the Oregon Basin domes Willwood strata overlap the "Fort Union" and Lance and lie on the Meeteetse; at the southern end of the structure the "Fort Union," which also rests on the Meeteetse, is cut by faults that have not affected the Willwood. Evidently, after folding and erosion of the dome, "Fort Union" sediments were deposited nonconformably on older beds. Continued or renewed uplift tilted and faulted the "Fort Union" and then, following another period of erosion, Willwood sediments spread over the surface of the truncated domes. Further arching of the domes tilted the Willwood eastward. Pierce and Andrews (1941, p. 108) believe that the major structural features in this portion of the border belt were formed after deposition of the "Fort Union."

The lowest Willwood, characterized by thick yellow sandstone layers, yields "Fort Union" plants (Hewett, 1926, p. 41) but no diagnostic mammals.

A ridge of red and drab Willwood abutting against a steep conical hill of "Fort Union" in sec. 13, T.50 N., R.100 W. (Hewett, 1926, p. 44) is evidence that the surface on which Willwood deposits accumulated had a relief of 50 to 100 feet.

(11) Two small outliers of the Willwood formation are preserved north of the Greybull River, in secs. 11 and 15, T.49 N., R.100 W.

(12) The section of the Willwood on the south side of the Greybull River from Tatman Mountain to Meeteetse exhibits important stratigraphic relationships of the formation. Below the Tatman beds that form the upper part of the mountain, the badland slopes are carved out of buff and bright-red upper Willwood deposits. To the southwest the Willwood rapidly becomes coarser and is nonconformable on the "Fort Union" (Hewett, 1926, p. 44, Pl. XVII). There is a remarkable exposure of this angular contact in sec. 7, T.48 N., R.99 W., (Pl. 3, fig. 1). The southwestern margin of the Willwood overlaps the "Fort Union" and lies on the Lance.

The variegated sediments on the lower slopes of Tatman Mountain are Lysite beds, the upper 325 feet are Lost Cabin (Sinclair and Granger, 1912, p. 62). Toward Meeteetse Lysite beds cover the Gray Bull and rest on "Fort Union" strata in a transgressive overlap that continues south at least as far as Cottonwood Creek (Sinclair and Granger, 1912, p. 61, Fig. 1). In the absence of evidence that the Gray Bull was eroded before deposition of the Lysite, it is probable the upper Willwood deposits spread marginward beyond the lower beds because the basin did not sink as rapidly as Willwood sediments accumulated.

The lenses of coarse conglomerates in the western extent of the formation (Pl. 4, fig. 3) from locality (12) to Neiber anticline (15) were probably restricted to graded river channels, while finer material accumulated locally on an irregular surface. The conglomerates are thickest and most numerous east of the Greybull River from Meeteetse to the point where the formation crosses the river. Those at the base of the Willwood in this region persist no more than a mile northeastward, grading into coarse sand and finally, farther northeast, into red-banded clay (Hewett, 1926, p. 40).

"When all the sedimentary and stratigraphic features of the formation in this region are considered it is very apparent that the coarse material represents an alluvial fan spread out on the border of an extensive alluvial plain at the point of emergence of one of the major rivers that supplied the sediments. The fan is roughly triangular, and is five or six miles wide at the base and eight or ten miles long, with the apex at the mouth of the ancient river. In the adjacent area on

the northwest, in Tps. 50 and 51N., R.99W., there appear to have been no major rivers during Wasatch [= Willwood] time, for the beds of conglomerate are thin and discontinuous and finer sediments predominate even near the base of the formation."

The coarse sediments of the Willwood and "Fort Union" are very similar, due, perhaps, to the derivation of some of the Willwood conglomerates from those of the "Fort Union." Quartzite and chert are common to both, but red granite pebbles, rare in the "Fort Union," are abundant in the Willwood, and limestone pebbles, characteristic of the Willwood conglomerates, are not found in the "Fort Union." Inasmuch as the granitic material in the "Fort Union" was eroded from pre-Cambrian rocks, Paleozoic limestones must have been exposed in the area whence the sediments were derived. The absence of limestone pebbles from the "Fort Union" evidently is a consequence of unfavorable conditions of deposition. The abundant conglomerate and sandstone lenses toward the western and southern margins of the Willwood suggest that the source of much of the Willwood now present in the basin lay to the south and west.

(13) Along the southern border exposures are poor, and the Willwood formation has been little studied. Because its lithic features resemble those of the upper part of the "Fort Union," the contact is difficult to locate. From the valley of Fifteen Mile Creek to Blue Ridge south of Gooseberry Creek Hewett mapped a bed of conglomerate containing reworked "Fort Union" pebbles as the base of the Willwood and traced this basal layer into an area where it is unconformable on "Fort Union" deposits (Hewett, 1926, p. 46).

(14) North, east, and southeast of the Squaw Buttes area of the Tatman formation badlands are cut in Lost Cabin beds of the Willwood (Sinclair and Granger, 1912, p. 62). The section exposed in the "honeycomb" topography north of Gooseberry Creek in the SE.$\frac{1}{4}$ T.47 N., R.97 W. (Pl. 6, fig. 4) comprises thick beds of lavender, red, gray, and white sandstone. Shale layers are rare.

For 10 miles or more along the southern margin of the Tatman formation the uppermost 100 feet of Willwood deposits is a sequence of yellow sandstone, red and gray shale, and thin lignitic lenses. Seventy five feet below the base of the Tatman is a bed of crumbly black carbonaceous shale 12 inches thick. The highest gray layer in the section is overlain by a mud-cracked sandstone that forms a rock terrace beneath a retreating scarp of brown lignitic Tatman shale. This sequence suggests an oscillation between Willwood and Tatman conditions, terminating in the conformable deposition of distinctive Tatman strata.

In the southwest corner of T.47 N., R.97 W., about 20 feet above the prominent carbonaceous layer in the upper Willwood, a 6-inch band of ferric hydroxide has been traced for several hundred feet. It is composed of spherical particles about 1.2 mm. in diameter with a radiating fibrous structure. The mineral is deep maroon and gives a red-brown streak. These characteristics indicate that the mineral probably is turgite ($2Fe_2O_3 \cdot H_2O$).

Investigation of bog iron ores shows that iron can be deposited as thin lenses of small lateral extent at the bottom of swamps, bogs, and sluggish water courses. Such deposits are usually most abundant along the margins of the water body and absent in the center. Iron is carried into solution in part by the action of organic acids from decaying vegetable matter. Bicarbonate waters also aid in this process.

FIGURE 1. THIN-BEDDED SANDSTONE IN TATMAN FORMATION

FIGURE 2. STEINKERNS OF GASTROPODS WEATHERED OUT OF FOSSILIFEROUS TATMAN SANDSTONE

FIGURE 3. FOSSIL GASTROPODS AND PELECYPODS PRESERVED IN TATMAN SANDSTONE

FIGURE 4. "HONEYCOMB" TOPOGRAPHY IN UPPERMOST WILLWOOD DEPOSITS
SE. ¼ T. 47 N., R. 97 W. One hundred feet of Tatman strata forms the less rugged escarpment at skyline.

The precipitation of iron hydroxide is accomplished by chemical and biological agencies. "Iron bacteria" Protozoa, Algae, and fungi play a large part in its deposition by absorbing the iron in solution and redepositing it as an iron compound. The fact that the iron-depositing organs require iron compounds in their life processes probably accounts for most of the iron precipitated by organisms. Under swamp conditions ferric hydroxide can be precipitated from ferrous carbonate solutions by oxidation and hydration, or by the activity of organisms. In the presence of much carbonic acid or decaying matter, iron may be precipitated as ferrous carbonate. This may be oxidized to ferric hydroxide or remain as a carbonate in the presence of much organic material. It has been claimed that such ferric hydroxides are colloidal complexes of indefinite composition. That bog iron ore deposits form in slack-water conditions explains the association of the band of ferric hydroxide with the thin lignitic layers in the upper part of the Willwood formation.

(15) Near the Big Horn River, the southern extent of the Willwood is dominantly thick yellow sandstone and dull-red beds. The largest fold within the main area of the Willwood, Neiber anticline, is 15 miles long, trends northwest, and is folded more sharply on the east side of the river (Hewett and Lupton, 1917, p. 139–142). Its south limb has a maximum dip of 21°, and its north limb 8°.

Neiber anticline is convincing proof of significant folding in the border belt after Willwood deposition. The more basinward structures may have been formed later than those nearer the mountains, or possibly all the structures of the border belt were folded at the same time, before deposition of the Willwood, and later movement acted upon pre-existing folds. These alternatives cannot be tested here because the basal contact of the "Fort Union" is not exposed, but observations at locality (10) support the latter.

(16) The inaccessible southeastern extent of the Willwood formation is mapped as lying on the Lance and Mesaverde (Geological Map of Wyoming, 1925). In the E.½ T.46 N., R.92 W., and the W.½ T.46 N., R.91 W., the Willwood consists of gray, lavender, and dark-red sandy beds eroded into "honeycomb" topography.

A few Gray Bull fossils were found in sec. 21, T.46 N., R.92 W. If the overlap shown on the Geological Map of Wyoming is correct, this is the only place in the basin besides locality (2) that Gray Bull beds cover the "Fort Union" formation.

(17) Gray shale of the "Fort Union" succeeded by distinctly red-banded shale and fine-grained sandstone of the Willwood are exposed in rounded badland hills along the Worland-Tensleep highway. Both formations dip gently basinward. In this facies of the Willwood buff beds are common, and sandstone channel deposits are scarce. Careful examination of the contact in the SW.¼ sec. 24, T.47 N., R.91 W., discloses a slight angular unconformity.

In the badlands 7 or 8 miles northwest of Worland red and buff Gray Bull beds, cut by numerous lenses of channel sandstone, contain abundant turtle and *Coryphodon* remains. Owing to the basinward dip of the strata these coarse sediments are higher in the formation than the beds east of Worland which were presumably nearer the source. Apparently the Willwood is fine-grained near its basal contact but coarser higher in the section.

(18) On the slopes of Sand Creek Divide the Willwood beds are predominantly

buff. At the north end of the divide, in the NE.¼ T.48 N., R.92 W., the change from the fine-grained, drab shale of the "Fort Union" to the red-banded Willwood is marked. The contact between the formations, though poorly exposed, appears to be conformable. About 300 feet above the contact, on the upper slopes of the divide, sandstone channel deposits are common in buff beds containing a few bright red layers.

(19) Dull-red, buff, and drab layers, dissected into badlands by Elk Creek and its tributaries, contain a Gray Bull fauna. Higher in the section to the west, toward Five Mile Divide, sandstone lenses are more abundant, and bright red bands conspicuous. Sinclair and Granger (1912, p. 62) believe the highest beds on this divide may be Lysite. About 5 miles west of the Big Horn River, between Five Mile Creek and the south fork of Elk Creek, a flexure in Gray Bull beds (Frisby dome or Elk Creek anticline) is further evidence of post-Willwood deformation. The structure, with limbs dipping about 8° (Sinclair and Granger, 1911, p. 108), was drilled in 1938 in sec. 11, T.49 N., R.94 W.

(20) One of the best exposures of the "Fort Union"-Willwood contact is on the south bank of Antelope Creek, on the line between secs. 29 and 32, T.51 N., R.93 W. (Pl. 3, figs. 3, 4). Sinclair and Granger (1911, p. 106) thought a nonconformity separates the formations, but examination of the contact does not confirm their interpretation. Even though all the beds are tilted basinward here, there is no evidence of an angular unconformity. The dip of the drab "Fort Union" changes gradually from 30° at the coal seams about 800 feet below the Willwood to 10° or 12° at the contact. Contiguous Willwood strata have the same dip. With continued decrease the dip of the Willwood becomes 1° or 2° about 1500 feet west of the contact. Willwood deposits begin with a few red and buff beds. Somber shale and carbonaceous layers in the lowest Willwood suggest recurring "Fort Union" conditions of deposition. Uplift of the Bighorn Mountains has flexed the strata in the basin so that the older beds nearer the mountains dip more steeply.

Along the Emblem-Garland road, between Dry and Whistle creeks, the Willwood consists mainly of buff and gray shale. Coarse sandstone is rare. Red beds are much more abundant higher in the section to the west on the eastern slopes of McCulloch Peaks. A "quarry" in a gray shale layer in the NW.¼ T.53 N., R.97 W., yielded *Diacodexis*, *Haplomylus*, *Hyopsodus*, *Paramys*, *Pelycodus*, a multituberculate, and a lizard. This assemblage is so similar to the one from the drab Willwood beds in the southeast corner of T.56 N., R.102 W., locality (5), that it probably indicates similar ecological conditions.

(21) At the southern end of Polecat Bench drab Willwood deposits resemble somber Polecat Bench sediments. In both formations sandstone channel deposits are common. About 4 miles northwest of Ralston the conformable contact between southwestward-dipping Willwood and Polecat Bench strata coincides with the Shoshone-Clark Fork divide. Higher in the section red and buff beds gradually become more numerous so that at the southernmost end of the bench the beds are more typically Willwood.

Jepsen has pointed out (1940, p. 227–228) that "attempts to fit distinguishable life zones or faunas into formational or member units, and to extend these coincident

units from one isolated area to another, are in many cases futile," and that none of the Paleocene faunal units "is stratigraphically coextensive with easily recognizable single lithic units of sufficient extent to have been called a formation, with the exception of the Lebo." Yet he has proposed (p. 232) the name Polecat Bench formation in place of Fort Union for the deposits in the vicinity of Polecat Bench above *Tricera-*

TABLE 2.—*Paleocene and Eocene formations and faunas in the Big Horn Basin*

Age	Faunas	Formation
Eocene Bridgerian	?	EARLY BASIC BRECCIA 60 feet
	(Green River flora)	TATMAN 870 feet
		transitional beds
Wasatchian	Lost Cabin Lysite Gray Bull	WILLWOOD 2500 feet
Paleocene	Clark Fork Silver Coulee Rock Bench Mantua	POLECAT BENCH 3500 feet

tops-bearing beds and below *Homogalax*-bearing beds. If Polecat Bench is to replace Fort Union as the name of a lithogenetic unit throughout the basin, the upper and lower limits of the formation should be defined lithologically as well as faunally.

Some of the lowest red-banded beds north of the Shoshone-Clark Fork Divide yield a late Paleocene mammalian fauna. For this reason Osborn (1929, p. 70) maintained that the "Big Horn Wasatch" begins at the base of the Clark Fork beds. But the Clark Fork fauna also occurs in drab shale underlying the Willwood southwest of McCulloch Peaks, demonstrating that the transition from drab Polecat Bench to variegated Willwood deposition was not synchronous throughout the basin. The formational boundary between them must, therefore, be distinguished clearly from the Paleocene-Eocene boundary based on faunas alone (Table 2). Fortunately there is no great discrepancy between the base of the Willwood formation and the Paleocene-Eocene boundary, but it is necessary for precise correlation to appreciate that deposition of Willwood sediments began in some places before the end of Paleocene time.

Two geologic maps of this region have been prepared since the publication of the Geologic Map of Wyoming (1925). (*See* Plate 7.) Jepsen (1930b, p 493–494, Fig. 2) used a faunal basis for dividing Paleocene and Eocene sediments; the lowest level containing *Hyracotherium* in the conformable series was the datum.

Stow (1938, Pl. 2) used lithology as the basis of his mapping when he plotted a boundary between Tongue River member of the Fort Union and the "Wasatch" (= Willwood), placing the base of the Willwood at the lowest persistent conglomerate (p. 736). He found that the Willwood is characterized by the sudden appearance

of hornblende and concluded that "heavy mineral assemblages can now be used as satisfactory 'second-order' bases for determining the age of unfossiliferous outcrops" (p. 761).

Because Stow attached an age significance to the distribution of heavy minerals, Jepsen (1940, p. 232) inferred that the appearance of green hornblende indicates the beginning of Eocene time, rather than the beginning of the Willwood as a lithic unit. If this inference were true there should be no discrepancy between Stow's lower limit of the hornblende-bearing beds and Jepsen's Eocene boundary based on the occurrence of Eocene mammals. However, Stow's formational boundary does not coincide with Jepsen's Paleocene-Eocene boundary because the base of the Willwood is the bottom of the lowest persistent conglomerate, a lithic feature. Hence it follows that green hornblende is not necessarily limited to the Eocene.

PALEONTOLOGY

Four faunas—the Clark Fork, Gray Bull, Lysite, and Lost Cabin—have been recognized among the mammalian fossils from the Willwood formation (Table 1).

The Clark Fork is the youngest Paleocene fauna, found only in the northwestern part of the Big Horn Basin. Its one distinctive genus is the oxyaenid creodont *Dipsalodon*. West of Polecat Bench diagnostic Clark Fork mammals have been secured from red-banded Willwood sediments, whereas southwest of McCulloch Peaks the Clark Fork beds are part of the Polecat Bench formation.

By definition Gray Bull beds are delimited by the presence of *Homogalax*, a primitive tapirlike perissodactyl. Jepsen (1930b, p. 494) has redefined the Gray Bull "to include the 'Sand Coulee beds', inasmuch as the genus *Homogalax*, whose supposed absence was the basis of distinction, has been found in typical 'Sand Coulee beds'." In the McCulloch Peaks area Gray Bull beds are about 2200 feet thick. The fauna is widely distributed throughout the basin and occurs near the base of the Jim Creek section of the Willwood in the North Fork region (Fig. 3, X). The Gray Bull has long been the best-known Early Eocene fauna, and it is to this very rich assemblage that our knowledge of Early Eocene vertebrate life is chiefly due.

The Lysite and Lost Cabin faunas were first differentiated among Wind River mammals. Later, equivalent assemblages were discovered in the Willwood formation. Granger (1914, p. 202) estimated the Lysite beds, characterized by the presence of another tapiroid ungulate, *Heptodon*, and the absence of *Homogalax* and *Lambdotherium*, to be 500 feet thick in the central part of the Big Horn Basin where they outcrop on all sides of Tatman Mountain and in the badlands to the south and extend east probably as far as Five Mile Divide. Beds near the top of Y. U. Bench (*see* Mackin, 1937, p. 859) north of the Greybull River may also be Lysite, but no diagnostic mammals have been identified. If the upper 150 feet of McCulloch Peaks is composed of Lost Cabin strata, as Wood *et al.* (1941, p. 25) have suggested, Lysite beds in this region must be very thin or absent, for Gray Bull fossils occur within 150 or 200 feet of the top of the peaks. No fossils of the Lysite fauna have been found in the Jim Creek section of the Willwood, although they may be present in the 225 feet of sediments between the known Lost Cabin and Gray Bull beds.

In the Big Horn Basin Lost Cabin beds, identified by the presence of *Lambdo-*

therium, the most primitive titanothere, compose the upper 325 feet (Sinclair and Granger, 1911, p. 108) of the Willwood that underlies the Tatman formation on Tatman Mountain and in the Squaw Buttes area, and the uppermost 150 feet of Willwood sediments on McCulloch Peaks (Wood *et al.*, 1941, p. 25). In the Jim Creek section Lost Cabin fossils occur 475 feet above the base of the Willwood.

The known Gray Bull fauna contains more different genera and species than either the combined Big Horn Basin and Wind River Lysite or Lost Cabin faunas. The Big Horn Basin Lysite has yielded about two thirds as many species of mammals as the Wind River Lysite, while only about one third as many species has been found in the Big Horn Basin Lost Cabin as in the Wind River equivalent.

The Gray Bull and Lost Cabin are easily recognizable faunas; the former contains 10 characteristic genera, and the latter 7. The Lysite, on the other hand, has yielded no diagnostic genera.

A numerical analysis of the Gray Bull, Lysite, and Lost Cabin mammalian faunas reveals several significant relationships. The Gray Bull is the most distinct from older faunas. Sixty per cent of its genera appear for the first time. Although this may be due in part to the limited knowledge of the Clark Fork fauna, it suggests that the greatest influx of new genera was at the beginning of the Eocene epoch. The Gray Bull is nearly twice as closely related to the Lysite as it is to the Clark Fork. Of the 35 genera whose earliest appearance is in the Gray Bull, 25 continue into younger faunas, demonstrating that the Gray Bull is correctly considered closely related to the latter Wasatchian (Early Eocene) faunas. These data are reassuring evidence that the Paleocene-Eocene division marks an important faunal change.

The least distinct assemblage, that from Lysite beds, is transitional between the Gray Bull and Lost Cabin, having about as many genera in common with the oldest as with the youngest Wasatchian faunas. In contrast to the new and distinctive forms into the Gray Bull fauna, only three genera first appear in the Lysite, and these continue into the Lost Cabin.

Seventy per cent of the Lost Cabin genera have been found in older Wasatchian faunas, whereas only 40 per cent of the Gray Bull mammals were derived from the Clark Fork. About 55 per cent of the Gray Bull genera and 85 per cent of the Lysite genera that occur in older faunas continue into younger faunas. On the contrary, only 35 per cent of the Lost Cabin mammals found in older beds continue into the Bridger. Furthermore, the Lost Cabin has the largest proportion of genera that do not continue into younger faunas—Gray Bull 35 per cent, Lysite 15 per cent, and Lost Cabin 70 per cent. Indeed, the Lost Cabin is almost twice as closely related (numerically) to older Wasatchian faunas as it is to Bridgerian faunal assemblages.

Most of the mammals found in the Willwood are crushed and fragmentary, and stained red brown. Many are encrusted with hematite. Associated material is more common in gray shale than in red (Sinclair and Granger, 1911, p. 117), and in sandstone layers fossils, though rare, are generally well preserved (Wortman, 1882, p. 141).

Almost all the fossils collected from the Willwood have been discovered by prospecting surface localities where "the mammal remains are rare, as far as known, and

are so sparsely scattered through the matrix that only accidental finds or concentration from long weathering and with erosion leads to any production" (Simpson, 1937, p. 29). Because Lysite and Lost Cabin beds are not easily accessible to the collector most of the specimens recovered are Gray Bull mammals. The most abundant of these are the remains of *Coryphodon*, a hippopotamuslike "subungulate." *Homogalax*, the earliest horse *Hyracotherium*, *Phenacodus*, a browsing archaic ungulate, *Hyopsodus*, a small, clawed condylarth, and *Sinopa*, the oldest hyaenodont carnivore are common in Gray Bull collections. Even though the larger forms are numerous because they are more easily preserved, their relative abundance as fossils also indicates that they were conspicuous members of the Gray Bull fauna.

Several "quarries" in drab Gray Bull beds (*see also* Jepsen, 1930a, p. 117–118) have yielded fragmentary jaws and skulls of small animals. In these localities "fossils are so concentrated in a local pocket that it is profitable to work the beds as a whole and recover fossils in place" (Simpson, 1937, p. 30). Specialized rodent-like multituberculates, *Diacodexis*, the oldest known artiodactyl, *Hyopsodus* and closely related *Haplomylus*, the squirrel-like rodent *Paramys*, *Pelycodus*, a lemuroid Primate, and lizards are most frequently associated. *Hyracotherium*, an insectivore *Diacodon*, the dermopterid *Plagiomene*, and *Peratherium*, a marsupial, were found in two quarries. Most of these mammals probably were mainly arboreal in habitus. Some were terrestrial.

Gray Bull quarry material is, as yet, too scanty to permit determining the real differences in composition between the surface and quarry faunas. But Simpson's interpretation (1937, p. 62–63) of analogous Paleocene collections from the Crazy Mountain field, Montana, the great bulk of which comes from quarries, is pertinent.

> "The 'surface' fauna, 90 percent carnivores and ungulates, is of more normal type, in comparison with Tertiary faunas generally, than are the quarry faunas. Its members average larger than those of the quarry faunas, and they are probably terrestrial for the most part. This appears to be a normal flood-plain facies."

His analysis of the quarry material

> "warrants the tentative conclusion that this fauna is largely arboreal, which is well in accord with the evidence that the quarries were in a swampy and heavily forested area and would go far toward explaining the unusual facies of the quarry faunas."

Besides a mammalian fauna, Gray Bull beds contain fossils of two giant flightless birds, *Diatryma* and *Omorhamphus*. Throughout the Willwood formation traces of turtles and crocodiles are common and often associated with *Coryphodon* both in fine-grained drab sandstone and in yellow sandstone channel deposits. The Willwood also yields amiid remains and locally abundant gar-pike scales.

The numerous species of gastropods from the Willwood are listed by Henderson (1935, p. 40–41).

The few fossil leaves found in the Willwood formation evince a continuation of the lowland, warm-temperate conditions of Paleocene time.

CONDITIONS OF DEPOSITION

Evidence indicative of the Early Eocene climate and topography in the Middle Rocky Mountain region has led to opposed interpretations. Fragments of gypsum

on the surface of the Willwood badlands, sometimes cited as indication of Early Eocene aridity, probably are the result of ground-water activity in the present arid cycle. Although Sinclair and Granger believed (1911, p. 113) that arkose in the Willwood suggests dry climate with rapid change in temperature, Berry has reported (Osborn, 1929, p. 65), on the contrary,

> "that in Lower Wasatch time the Fort Union flora persisted over the Rocky Mountain region. This implies that the climate was then prevailingly warm temperate, but that there were occasional incursions of trees of subtropical types."

A persistent view in older literature, that the Rocky Mountains reached great heights in early Cenozoic time, seems to be corroborated by the discovery of deposits of Eocene till. Indeed, it has been contended that

> "during the Eocene there must have been mountains 12,000 to 15,000 feet high. It is safe to imagine a landscape with alpine glaciers as picturesque and as bold as any that have ever existed in the Rocky Mountains" (Atwood and Atwood, 1938, p. 962).

In this interpretation the nature of the flora and fauna is not considered. And yet this information has so profound a bearing on the problem that any concept that disregards it is faulty at its source. High mountains would have affected the climate, and a change in the climate would be reflected in the paleontologic record. It is significant, therefore, that the Early Eocene flora is a lowland type, characteristic of a warm-temperate or subtropical climate, and exhibits no important change from Paleocene to Eocene. Remains of amiids, gar-pikes, and lizards in both Paleocene and Early Eocene sediments also suggest a similar environment. The mammalian fauna in no way contradicts this record. Moreover, the presence of the same species of Early Eocene mammals in more than one intermontane basin demonstrates that there were no topographic barriers impeding the migration of lowland mammals.

These observations accord with the view that antecedent Cretaceous conditions continued during the early Cenozoic. Although the bordering ranges were intensely deformed at this time and eroded to their pre-Cambrian cores, the orogeny was slow enough to permit erosion to maintain a mature stage of topography. There were no mountains high enough to cause a marked change in the warm-temperate to subtropical climate (though such a change is postulated by some authors to account for the demise of the dinosaurs). Concomitant downwarping of the Big Horn Basin was accompanied by fluvial and lacustrine aggradation in a forested lowland area probably less than 1500 feet above sea level. This interpretation agrees with Mackin's (1937) analysis of the geomorphic history of the region.

Until about 1900, most of the early Cenozoic sediments in the Rocky Mountain region were assumed to be lacustrine deposits, but evidence of a fluviatile origin has since been found both in the nature of the sediments and the mammalian faunas. The fluviatile features of the Willwood were first recognized by Fisher (1906) and Loomis (1907). Among the most convincing proofs that Willwood sediments were deposited in channels and on flood plains of sluggish streams is the fact that the coarse deposits are concentrated in long bands having winding courses, and the bands occupy different positions at different depths. This arrangement suggests that the sand and gravel mark the channels of overloaded, braided, and constantly shifting streams.

Of significance, too, is the lenticular shape of the shale layers "varying from a few inches in thickness, with little horizontal extent, to strata from 18 to 50 feet in thickness, traceable sometimes for several hundred yards to a mile or more" (Sinclair and Granger, 1911, p. 114). This conclusion is also substantiated by the marked contrast between the Willwood and the thin-bedded, uniform lacustrine deposits of the Green River and Tatman formations. The abundant mammal remains in the Willwood and the paucity of fossil mammals in the Green River and Tatman further emphasizes the difference between fluviatile and lacustrine sediments.

Two theories have been proposed to explain the origin of sandstone dikes. Wanless (1923, p. 256) described a dike in the White River group that was unmistakably derived from beds nearly 200 feet higher in the section and interpreted the fissures to have been cracks open to the surface, analogous on a very large scale to mud cracks. Some sandstone dikes in the Willwood, on the other hand, are clearly traceable downward into sandstone lenses (Pl. 4, fig. 2). These structures "may have been forced up as quicksand through cracks produced by earthquakes" (Sinclair and Granger, 1911, p. 112) accompanying the deformation which produced the local folds and faults (Pl. 4, fig. 1) in the Willwood.

The stratigraphic relationships of the Lower Eocene sediments in the Wind River Basin and in the Big Horn Basin differ in two respects. Along much of its periphery the Wind River formation is nonconformable on rocks as old as pre-Cambrian, whereas the Willwood rests on the Polecat Bench formation in most of its marginal exposures. Furthermore, the Wind River strata covering most of the surface of the Wind River Basin are younger than the Willwood that outcrops extensively in the central part of the Big Horn Basin. Only on some of the high divides are beds of the Willwood preserved that correlate with the Wind River formation.

Even though these facts may suggest that each basin has had a somewhat different history of downwarp and aggradation, the differences in the two basins are related, for the most part, to the process of excavation of the Cenozoic deposits by the Big Horn drainage system.

Along the western margin of the Big Horn Basin, upper Willwood strata equivalent to the Wind River overlap older beds and lie on Cretaceous rocks. Consequently, there is a nonconformity in both basins below variegated sediments of about the same age. The present difference in extent of marginal overlap is apparently due to the amount of waste-fill eroded from each basin. In the Big Horn Basin most of the younger beds which originally extended marginward have been removed, while in the Wind River Basin degradation by the headwaters of the Big Horn drainage has not advanced so far, preserving more nearly the original condition of aggradation. The lower Willwood beds exposed by the extensive erosion of the Big Horn Basin are conformable on older deposits in the central part of the basin. Wind River strata equivalent to the lower Willwood may lie buried in the Dry Cottonwood syncline along the north side of the Wind River Basin (Bauer, 1934, p. 673), for deposits of this age are present in the northwestern part of the Wind River Basin (Love, 1939, p. 58–63). Thus, sediments accumulated in both basins in earliest Eocene time. As the basins filled with detritus, the deposits spread laterally across truncated structures. Subsequent degradation carried away most of the Lower

Eocene sediments from the periphery of the Big Horn Basin. Further erosion in the Wind River Basin will produce a similar situation.

TATMAN FORMATION

GENERAL STATEMENT

Fisher (1906, p. 34) first reported soft brown shale and yellow sandstone above the red-banded Early Eocene deposits in the vicinity of Squaw Buttes and on Tatman Mountain; he estimated their thickness at 600 feet. In a stratigraphic section of the west end of Tatman Mountain published by Loomis in 1907 (p. 360) these beds were recorded as 730 feet of "clayey shales, brown and gray" overlain by 30 feet of coarse sandstone.

In 1911 Sinclair and Granger (p. 109–111) briefly described 600 feet of "post-Wind River lignitic shales" on the north and northeast sides of Tatman Mountain, suggesting that they might be equivalent to the Bridger of the Beaver Divide section in the Wind River Basin. Although Sinclair and Granger discussed the gravels capping the bench, they did not introduce Tatman Mountain gravels as a formal stratigraphic name. (*See* Wilmarth, 1938, p. 2120.)

Tatman formation was proposed in 1912 (Sinclair and Granger, 1912, p. 62–63) for the deposits of

> "yellowish shales, yellow-brown and gray sandstones and lignite beds overlying the red-banded Lost Cabin clays typically developed on Tatman Mountain, but occurring also on Squaw Buttes and on the high divide between Fifteen Mile and Gooseberry creeks both to the north, south, and west of the buttes. Wherever the contact is exposed, the Tatman formation appears to be conformable with the Lost Cabin beds below. It has not been found north of the Greybull River and seems to have been entirely eroded from this portion of the basin."

The name Tatman formation has been rejected by the United States Geological Survey (Wilmarth, 1938, p. 2119), but no reason for this decision is given.

Hewett and Lupton (1917, p. 29) apparently misinterpreted the definition of the Tatman formation for they stated that the "Wasatch" contains "the faunal zones recently given the names Greybull, Lysite, Lost Cabin, and Tatman by Sinclair and Granger." In 1926, however, Hewett (p. 61) referred to the five faunal zones of the "Wasatch"—the Clark Fork, Sand Coulee, Greybull, Lysite, and Lost Cabin—but did not mention the Tatman as a faunal unit. In fact, he noted that "the 'border Wasatch' closely resembles the 'Tatman formation' in lithologic features."

The Tatman formation is preserved in three areas in the Big Horn Basin. The shape of that remnant forming the upper 650 to 700 feet of Tatman Mountain (Pl. 7) is based on the topographic contours given by Fisher (1906, Pl. III), supplemented by field observations. On the southwestern border of the basin, between Grass Creek and Cottonwood Creek, Tatman deposits consist of a maximum of 150 feet of soft brown carbonaceous shale and buff sandstone. The greatest extent of the Tatman, in the vicnity of Squaw Buttes was mapped (Pl. 7) by plane table and alidade; accuracy was increased by the use of the Wyoming State Highway Department county maps as a base.

STRATIGRAPHY OF THE SQUAW BUTTES AREA

General statement.—In the Squaw Buttes area 90 square miles of nearly horizontal Tatman strata (Pl. 5, fig. 1) are eroded into plateau topography that contrasts

sharply with the brightly colored badlands below. Squaw Buttes rise 400 feet above the highest successive erosion level cut by the intermittent streams that drain the region.

Sagebrush-grass range type of vegetation is more abundant on the flat upland surface than in the surrounding badlands, affording meager grazing for cattle and sheep in the summer and fall.

Tatman strata dip gently toward the center of the structural basin beneath Squaw Buttes. In the northeast the dip is about 2° SW., in the vicinity of the buttes 2° E., along the southwestern margin 4°–5° NE., and along the southern margin it is 1°–2° N. As a consequence the youngest beds in the basin are preserved here.

Tatman formation.—The columnar section (Fig. 4), from the base of the Tatman in the NE.¼ sec. 2, T.48 N., R.98 W., to the highest beds preserved beneath the basic breccia capping Squaw Buttes, was measured by hand leveling. In the recorded section the formation is 867 feet thick. Measurement of minor units is made difficult by slopewash and talus covering the outcrops. The lower 100–200 feet of the formation is well exposed locally along the northern, eastern, and southern margins of the area; the upper 300 feet crops out on Squaw Buttes (Pl. 5, fig. 2).

The Tatman formation comprises a series of laminated, brown carbonaceous shale and fine-to medium-grained sandstone layers in alternating units 10 to 80 feet thick. Thin buff marlstone beds are occasionally associated with the sandstone.

Most of the sandstone is fine-grained and thin-bedded (Pl. 6, fig. 1). Its stratification is due to light-colored layers of clay, quartz, and mica, seldom more than 1 or 2 mm. thick, separated by dark carbonaceous bands, sometimes only a film of carbonaceous material and mica flakes. No gradation in grain size has been observed within the laminations. Although such thin, persistent strata imply absence of strong currents during deposition, some thin-bedded sandstone is minutely cross-bedded, and much of it is ripple-marked. The presence of considerable clay renders the sandstone layers relatively impervious. Hence ground water has had slight chance to introduce calcareous cement, and the beds are but little lithified.

Fossil pelecypods and gastropods, preserved as steinkerns (Pl. 6, figs. 2, 3), abound in the sandstone.

Two beds of coarse arkose have been found in the Tatman formation. Each is about 25 feet thick and composed of poorly sorted, angular grains. Most of the material below 1 mm. in diameter is quartz and unaltered white and gray feldspar, but that between 1 and 2 mm. is principally gray and black chert. The largest fragments in the arkose are about 5 mm. in diameter.

Dr. M. H. Stow (personal communication) reported that the heavy minerals of the Tatman sandstone he examined were similar to many of his samples from the Willwood (Table 3). Sinclair and Granger (1912, p. 63) had also recognized this similarity and suggested that the Tatman and Willwood sediments were derived from the same source.

All the shale of the Tatman formation is carbonaceous according to White's nomenclature (Twenhofel, 1932, p. 351). Usually it is distinct from the sandstone layers, with little evidence of gradation, though some thin shale beds occur within the larger sandstone units.

There are two kinds of carbonaceous shale in the Tatman, each containing variable amounts of mud: (1) Brown and black humic sediments, products of peat formation in which plant fragments are visible. Leaves are often preserved as a carbonized film or as impressions, and in several instances black lignite layers have been formed. (2) Sapropelic or bituminous sediments, composed largely of products of putrifaction, originating in stagnant water, and yielding few traces of carbonized plant

TABLE 3.—*Heavy-mineral analysis of Willwood, Tatman, and Early Basic Breccia samples*

	Colorless Garnet	Red Garnet	Zircon	Tourmaline	Staurolite	Kyanite	Amphibole	Pyroxene	Rutile
1	Flood	Flood	Rare	Rare	Common	Common	Common		
2	Flood	Flood	Rare	Rare	Common	Rare	Rare		Rare
3	Flood	Common	Rare	Rare	Common	Rare	Few grains		Rare
4	Flood	Flood	Rare	Rare	Common		Few grains		Rare
5	Few grains	Few grains					Flood	Flood	

1. Lower Willwood beds in the northern part of the Big Horn Basin.
2. Willwood formation, summit of the west peak, McCulloch Peaks.
3. Highest Tatman strata preserved on the east end of Tatman Mountain.
4. Uppermost beds of the Tatman formation, Squaw Buttes.
5. Early Basic Breccia, Squaw Buttes.

remains. The bituminous type in the Tatman formation is a very low-grade oil shale, finely laminated and fissile ("paper shales").

In bituminous sediments ostracode shells are abundant and usually preserved on the bedding planes. Scattered throughout the ostracode-bearing shale are scales, teeth, and bones of small fish. Where plant debris is common and ostracodes absent, gar-pike scales and traces of crocodiles and turtles frequently occur.

Small chert concretions, from $\frac{1}{2}$ to $2\frac{1}{2}$ inches long, have been found in the oil shale. Some are flat, others cylindrical or ellipsoidal. Ostracodes are present in the chert but are much more abundant in the layer of calcareous clay coating each concretion.

The contact between the Willwood and Tatman appear to be conformable. At the northern escarpment of the Squaw Buttes area the lowest 100 feet of Tatman strata is white and gray sandstone and clay, and a few brown carbonaceous layers. Although the soft Tatman sandstone is quite distinct from the yellow channel deposits of the Willwood, the typical Tatman features begin less abruptly than along the southern margin.

The lowest 100 feet of the Tatman at the southern margin is mainly brown shale, some of which is lignitic, overlying an extensive mud-cracked sandstone that was mapped as the base of the formation. Within this shale unit fragmentary fossil leaves are abundant. About 100 feet above the base a hard sandstone containing a great many *Goniobasis* and *Unio* forms the lowest rock terrace in the region. Another bed of sandstone 25 or 30 feet higher makes a second terrace. Above this, in a retreating scarp, is a bed of buff marlstone.

A 50-foot lens of red and gray shale 200 feet above the base of the formation, in sec. 12, T.47 N., R.98 W., has been traced for several miles near the western margin.

Brown carbonaceous shale above and below the variegated beds shows that the lens resulted from a temporary change in conditions of deposition.

Three hundred feet above the formation's base in the measured section there is a 5-foot bed of lignite, the thickest yet found in the Tatman.

Very homogeneous, massive buff marlstone (*see* Bradley, 1931, p. 6–7) crops out on the tableland east of Squaw Buttes. A few silicified ostracodes occur on the weathered surfaces of the marlstone fragments and in a polished section of the rock. No other organic remains have been identified.

Early Basic Breccia.—Squaw Buttes are capped by about 65 feet of brown basic breccia (Table 3; Pl. 5, fig. 2) that is correlated with the Early Basic Breccia overlying Tatman strata in the Absaroka foothills. The unsorted, angular fragments (Pl. 5, fig. 3) demonstrate that the agglomerate is not reworked material eroded from the Absaroka volcanic rocks. If correctly correlated this outlier is the farthest east any of the Absaroka series has been traced. That it undoubtedly is Early Basic Breccia agrees with the fact that this unit is the most extensive of the Absaroka volcanics.

TATMAN MOUNTAIN SECTION

In its type locality on Tatman Mountain the Tatman formation is 650 to 700 feet thick and contains considerably more lignite than in the Squaw Buttes section. Conversely, there is no oil shale. A coal seam on the south side of the mesa has been worked by local ranchers. At the east end of the great bench a bed of soft drab shale consists almost entirely of comminuted shells of gastropods, pelecypods, ostracodes, and phyllopods. Contiguous Willwood and Tatman strata are obscured by colluvium except at the west end of Tatman Mountain where the transition between the formations is seen to be more gradual than at the southern margin of the Squaw Buttes area. Red beds and carbonaceous shale alternate for 150–175 feet.

Tatman Mountain is capped by 30 feet of gravel "composed largely of basic igneous rock types, carried by the Greybull River from the Absaroka Mountains" (Mackin, 1937, p. 860–861). Mackin inferred

> "that the gravels on Tatman Mountain were deposited, not by aggrading streams, during, or at, the culmination of the early Tertiary period of basin filling, but by the degrading Greybull River, during the current period of excavation. . . . The former height of the basin fill . . . was probably much higher than Tatman Mountain and, therefore, . . . the Tatman surface, like the other benches examined, marks one of the degradational stages of the basin."

The fact that on Tatman Mountain the Early Basic Breccia is not present and the Tatman formation is about 200 feet thinner than in the Squaw Buttes area substantiates this inference.

PALEONTOLOGY

Fossils are plentiful in the Tatman formation, but most of them are poorly preserved and of little diagnostic value.

In shale beds fragmentary remains of fish, crocodiles, and turtles have been found.

Abundant gastropods and pelecypods occur in some sandstone layers (Pl. 5, fig. 3) and occasionally in soft shale. Stanton (Fisher, 1906, p. 34) issued the first report on fossils from the Tatman formation:

"The small collection [found in the Squaw Buttes area] contains many internal casts of freshwater fossils belonging to the genera *Unio*, *Viviparus*, and *Goniobasis*. Of the last named there are imprints of the exterior which permit identification with *G. tenera* Hall, an Eocene species. The *Unio* has about the size and proportions of *U. haydeni* Meek and the *Viviparus* resembles *V. wyomingensis* Meek, but in neither case can positive identification be made with such material, as there are Laramie species so closely resembling these that they could not be discriminated from the casts alone. I think the horizon is Eocene, but I am unable to determine from these fossils whether it is Wasatch or Bridger."

Mollusks found in sec. 23, T.48 N., R.98 W., and sec. 29, T.47 N., R.97 W., have been questionably referred to these species by Dr. L. S. Russell. Regarding the gastropod species he has stated (personal communication):

"*V. myogensis* has been reported from various Eocene horizons in Wyoming and Utah, including Gray Bull and Bridger. Your specimens appear intermediate in size between those of the two horizons mentioned. *Goniobasis tenera* is one of a large group of Eocene species or subspecies, the members of which are differentiated mainly by their ornamentation. *G. tenera* has been recorded from the Gray Bull, Wind River, and Bridger."

These data suggest that the Tatman is not younger than Bridgerian.

Ostracodes from the bituminous shale have been examined by Dr. C. I. Alexander who believes (personal communication) they show that the Tatman shales were deposited in shallow, more or less temporary or seasonal lakes.

Carbonized leaves are common in the humic shale, yet few good specimens have been collected. The best fossils, from beds at the base of Squaw Buttes, were examined by Dr. Erling Dorf who reported (personal communication) that the flora is a lowland forest type that lived in a warm-temperate to subtropical climate. It is an early Bridgerian assemblage, indicating that the Tatman correlates with the Early Basic Breccia near Valley, Wyoming, the Aycross formation in the northwestern part of the Wind River Basin, and the Green River formation at its type locality near Green River, Wyoming.

COMPARISON OF THE GREEN RIVER AND TATMAN FORMATIONS

Abundant carbonaceous shale, persistent lithic units, and a paucity of coarse sandstone distinguish Tatman deposits from the Willwood and Bridger. On the other hand, a comparison of the sediments and fossils of the Tatman and Green River formations reveals that these two were deposited under similar conditions.

The Green River lacustrine deposits accumulated in two large intermontane basins, one in southwestern Wyoming and the other in Utah and Colorado south of the Uinta Mountains. Shoreward, the unique, finely laminated oil shale grades into a thinner, coarser shore facies which, in turn, interfingers with fluviatile Wasatch and Bridger sediments.

In the Green River Basin in southwestern Wyoming the Green River formation is 1500 feet thick; its shore facies is developed toward the Uinta Mountains to the south and the Wind River Mountains to the north. When the Green River lake spread across the lowland where fluviatile sediments had been accumulating, light-brown Tipton shale, sandstone, and ostracode-bearing limestone were deposited conformably on the Hiawatha member of the Wasatch. Deposition of variegated Wasatch sediments continued only at the margin of the basin on flood plains not transgressed by the lake. Then fluviatile conditions encroached upon the basin as the lake receded temporarily, covering the marginal portion of the Tipton tongue

with the red-banded Cathedral Bluffs tongue (Middle Eocene) of the Wasatch. At the center of the basin Laney oil shale succeeded the Tipton shale. Another expansion of the lake gradually extended lacustrine deposits shoreward, and low-grade Laney oil shale buried the distal part of the Cathedral Bluffs tongue. With the introduction of much gray clay and sand Laney sediments graded laterally into upper Cathedral Bluffs deposits. Throughout the basin the Laney shale member was replaced by buff sandy limestone and sandstone of the Morrow Creek member of the Green River formation in which are preserved abundant plant remains. In the northern part of the basin the Morrow Creek spread marginward even farther than the Laney shale and was deposited directly on the Cathedral Bluffs tongue of the Wasatch. While Morrow Creek sediments were accumulating in the lake, deposition of the Bridger began on shore. Gradually Bridger deposits encroached upon the lake basin until they covered the entire region, so that in the center of the basin middle, not lower, Bridger sediments were deposited on the Green River formation.

This summary of the Green River formation in the Green River Basin is based on the studies of Sears and Bradley (1924), Bradley (1925; 1926; 1931), and Nace (1939).

The Tatman formation possesses many features similar to those of the upper and lower Green River deposits, but it has little in common with the rich oil shale members of the middle part of the Green River. A detailed comparison discloses that the Tatman most closely resembles the shore facies of the lower and upper units.

In its general aspects, particularly the relationship of sandstone and shale units, the Tatman is like the shore facies in northwestern Colorado which Bradley (1931, p. 14) has described as follows:

> "Nearly 50% of the shore facies north of Deep Channel Creek is sandstone. The sandstone beds form groups 10 to 80 feet thick, which alternate with shale units of about the same size. . . . Most of the sandstone is fine or medium grained, but locally it is coarse grained and contains varicolored chert pebbles as much as half an inch in diameter."

The sandstone of the Tipton tongue farthest from the source of sediments is "usually limy, micaceous, very fine-grained, and in thin, relatively persistent beds. Rarely this fine limy sandstone shows cross-bedding on a minute scale" (Bradley, 1926, p. 125) as do some of the thin-bedded sandstone layers of the Tatman. Mud cracks and ripple marks, common in the lower part of the Green River and in the shore facies (Bradley, 1931, p. 10, 14), are also preserved in some of the Tatman sandstone. Nearer the source, the sandstone of the Tipton tongue, like the coarsest sediments in the Tatman, contain pebbles and coarser sand grains, largely of quartz and feldspar, that are either sharply angular or only slightly rounded. The soft thin-bedded sandstone and associated marlstone of the Tatman is very similar to the Douglas Creek member of the Green River in the Piceance Creek section, about 20 miles west of Meeker, Colorado, and at the top of Douglas Pass, in the eastern half of T.5 S., R.102 W., Colorado.

Unlike the typical lacustrine deposits of the middle part of the Green River, the Tatman contains many layers of lignite and beds of brown carbonaceous shale in

which leaves are preserved. Fragmentary plant remains, mostly stems and ribs of leaves, are rather sparingly but uniformly distributed through the lower part of the Green River formation in northwestern Colorado and adjacent Utah (Bradley, 1931, p. 10). Well-preserved leaves are found in the upper part of the formation in this region. In Utah the tongue of the Green River (1931, p. 17) which consists mainly of light chocolate-brown, ostracode-bearing shale contains two thin beds of coal. In the Green River Basin leaves are common in the Morrow Creek member and sporadic in the Tipton tongue.

"A few thin beds of carbonaceous shale composed entirely of carbonized plant remains also occur in the Green River formation in this area. The floral evidence from these rocks thus appears to be in accordance with the hypothesis that they were deposited near the margins of the ancient lake" (Bradley, 1926, p. 126).

Especially characteristic of the Green River formation is its oil shale; hence the low-grade oil shale of the Tatman formation is of interest in substantiating a comparison of the two formations. Like the rest of its sediments, the Tatman oil shale is similar to the sapropelic deposits in the shore facies of the Green River. Bradley has described the latter as follows (1931, p. 22):

"Beds of ostracode-bearing limestone and ostracode-bearing shale, also in the shore facies of the formation, are buff, yellowish brown, or even dark chocolate-brown with the organic matter that is uniformly diffused through them. They will yield oil in quantities ranging from 5 or 6 to perhaps 20 gallons to the ton."

Bituminous shale near the base of the Green River formation on the east side of Carr Creek, about 25 miles northwest of DeBeque, Colorado, is very much like the ostracode-bearing oil shale in the Tatman.

The Chert concretions in the Tatman bituminous shale resemble those described by Bradley (1931, p. 37).

"Concretions of chaledonic quartz are not particularly common but were found in several oil-shale beds, some of which are rather low grade. These concretions like those of calcite, are roughly ellipsoidal. They range in length from about 5 millimeters to 5 centimeters."

Unlike the Tatman concretions, however, each one from the Green River is coated with a layer of pyrite.

The Green River contains many beds of oölitic limestone, marlstone, and reefs formed by calcareous algae, in which ostracodes often abound. Such sediments are present both in the lower part of the formation and in the shore facies, but limestone and algal reefs are rare in the Morrow Creek member in the Green River Basin. In the Garden Gulch member south of the Uintas, as in the Tatman formation, marlstone is the only limy deposit.

Goniobasis, *Viviparus*, and *Unio* are preserved in the lower Green River deposits and in the Tatman sandstone layers.

Ostracodes are most abundant in the lower beds and in the shore facies of the Green River, usually in limestone layers, though occasionally they are present in shale and in sandstone strata. Shale in the shore facies containing fragmentary leaves, ostracodes, and *Estheria* (Bradley, 1931, p. 14) calls to mind the soft shale in the Tatman formation at the east end of Tatman Mountain.

Bradley (1925, p. 250) has reported that

"such vertebrate fossils as crocodiles and river turtles have been found only in known shore phases of the Green River . . . the bony scales of *Lepidosteus* and fragments of rib bones, rays and vertebrae of other fish are of very common occurrence throughout most of the Tipton shale member and Tipton tongue of the Green River formation in the Green River Basin."

There are similar fossils in the Tatman formation.

That the Tatman formation is comparable to the shore facies of the Green River is emphasized by the description (Sears and Bradley, 1924, p. 98) of the Laney shale member. In the center of the Green River Basin the Laney shale is finely laminated oil shale.

"Near the mountains it is prevailingly buff and much of its shale is limy and poor in oil-yielding organic matter. Although sandstones are numerous, only one conglomerate was observed.... This conglomerate lens . . . passes rapidly northward into a coarse-grained sandstone with a limy cement. . . . Two or three thin beds of coal and numerous beds of partly humified plant remains occur in the Laney shale several hundred feet above the base."

The red-banded shale in the lower part of the Tatman formation may be comparable to the Cathedral Bluffs tongue of the Wasatch, but erosion has so reduced the Tatman that its variegated beds cannot be traced westward. If, as in the Green River Basin, red and gray sediments were accumulating beyond the region of lacustrine deposition, these red-banded beds might have resulted from a temporary recession of the Tatman lake accompanied by a basinward spreading of fluviatile deposits, after which Tatman conditions were re-established. Possibly no such extension of the red-banded deposits across the basin ever occurred; the change in conditions of deposition may have been local.

ORIGIN OF THE TATMAN FORMATION

In marked contrast to the channel sands and variegated shales of the Willwood the Tatman formation consists of alternating persistent carbonaceous shale and fine-grained sandstone units. The evidence adduced indicates that most of the Tatman sediments were deposited in a uniform and widespread environment of a forest swamp and in the open waters of a shallow lake. No near-by mountains were undergoing rapid erosion. In the swamp the lignites and much of the brown carbonaceous shale accumulated. In the open water that from time to time displaced the wooded swamp, persistent fine-grained sandstone and laminated oil shale were deposited. This interpretation is corroborated both by the contrast between the Willwood and Tatman lithic features and by a comparison of the Tatman formation and the shore facies of the Green River. Bradley (1926, p. 125) found that the numerous stream-channel deposits in the Green River formation become evenly bedded, finer-grained, and thinner away from the source, eventually grading into finely laminated shale. He inferred that the shore line of the lake probably should be placed where cross-bedding in the sandstone lenses becomes reduced greatly in scale and the greater portion of the sand assumes a distinct and fairly regular bedding. According to this inference most of the sandstone in the Tatman formation is of lacustrine origin.

There is no direct evidence of the source of the clastic sediments, but since Tatman and Willwood heavy minerals are similar and the source of the Willwood in the Squaw Buttes area lay to the south and west, much of the Tatman sandstone probably was derived from that direction. The arkoses in the Tatman may have been

deposited during periods of flood which, at least twice, swept coarse, feldspar-rich sands from the uplands to the west across the lake basin.

Nor do Tatman deposits yield any certain indication of the extent of the lake. The centrical dips around the Squaw Buttes area and the more sandy basal portion of the formation along the northern margin do suggest that the middle of the lake was near the southern margin of the Squaw Buttes area. That the north shore was near Tatman Mountain may explain the absence of oil shale in the type section. This impression is strengthened by the absence of Tatman deposits on McCulloch Peaks, about 1000 feet higher than the base of the Tatman formation on Tatman Mountain.

The flora preserved in the Tatman and Green River formations lived in a lowland area, in a warm-temperate to subtropical climate, a continuance of the lowland environment of Late Cretaceous, Paleocene, and Early Eocene time. The maintenance of similar conditions of deposition throughout the accumulation of 867 feet of Tatman strata suggests downwarping concomitant with the deposition of the sediments.

During early Cenozoic time the master stream of the basin's drainage system may have flowed northward through the gap between the Beartooth and Pryor mountains. Damming of this stream would have made a lake in the southern part of the basin. Nevertheless, the absence of evidence of faulting or of debris, such volcanic material, which could have dammed the stream, suggests that local downwarping produced the Tatman lake basin. Because the Tatman formation accumulated in a lowland environment, perhaps 1000 feet above sea level (*see* Bradley, 1930, p. 89), the change from Willwood to Tatman conditions of deposition could have been effected by much less depression of the basin floor than would have been necessary to produce a lake basin if the region were several thousand feet above sea level and surrounded by high mountains.

SOUTHWESTERN BORDER OF THE BIG HORN BASIN

STRATIGRAPHY

Willwood formation.—Nearly horizontal layers of variegated shale along the eastern slopes of the Absarokas yield an Early Eocene mammalian fauna (Pierce and Andrews, 1941, p. 137). In a belt of badlands between Grass Creek and Cottonwood Creek these Willwood strata, 125 to 250 feet thick, comprise bright red, lavender, and gray sandy shale and white and yellow sandstone. Conglomerate lenses are common though the pebbles are seldom more than 4 inches in diameter. In general the sediments resemble Willwood beds near the top of McCulloch Peaks and at the west end of Tatman Mountain. Pierce and Andrews (1941, p. 136) have reported that

> "north of the Greybull River, in T.48 N., R.103 and 104 W., the lower 300 feet of the Wasatch [= Willwood] consists of red shale and sandstone. These beds are overlain unconformably by a much thicker sequence of sandstones, shales, and clays that are a dull blue-gray in color. . . . The blue-gray beds dip less than 5° to the west and northwest and the lower red beds dip as much as 20° in about the same direction."

In this section, lenses of conglomerate that may have been derived in part from the "Fort Union" contain boulders a foot in diameter (p. 135–136). Well-preserved

Sundance fossils redeposited in the Willwood reveal that rocks as old as Jurassic were being eroded not far away at the time the lower Willwood was deposited (p. 137).

Tuff in the Willwood in this region (Pierce and Andrews, 1941, p. 137) and in Wind River deposits in the Wind River Basin (Sinclair and Granger, 1911, p. 93–94) substantiates the suggestion of Early Eocene volcanic activity based on the sudden appearance of hornblende in Willwood sandstone.

Pierce and Andrews (1941, p. 152) believe that the principal folding here occurred after the "Fort Union" was laid down. The Willwood was then deposited on truncated folds of the border belt on a surface with 200 to 300 feet of relief (p. 135). Coincidence of the relief with the anticlines suggests that deformation may have continued during Willwood deposition. Subsequently, Willwood strata were broadly warped, perhaps by the same movement that arched the Willwood on the Oregon Basin domes and Neiber anticline. As a result, the base of the formation rises from 6000 feet near Cottonwood Creek to 6800 feet 9 miles north. Three miles farther north the base is 6600 feet above sea level and then rises to 7000 feet near the Wood River.

Near the head of Little Prospect Creek, in the northern part of T.45 N., R.99 W., two faults offsetting the Willwood and Early Basic Breccia demonstrate post-Early Basic Breccia deformation which may have occasioned the warping of the Willwood.

East of the Absaroka foothills several isolated remnants of the Willwood rest on beveled strata ranging from Mesaverde to "Fort Union." These are substantial evidence that the red-banded beds under the volcanic series were once continuous with the Willwood in the central part of the basin. Further indication of a former connection is the coarse basal conglomerate near the Greybull River in both areas. It is entirely possible that the variegated sediments spread marginward across the border belt only after much of the Willwood had accumulated in the deep central basin. The transgressive overlap of the Lysite beds near Meeteetse (locality 12) and the resemblance of the marginal Willwood and the upper Willwood beds on McCulloch Peaks and Tatman Mountain (*see* Hewett, 1926, p. 41) favor this view.

Tatman formation.—Beneath the Early Basic Breccia from Cottonwood Creek to Grass Creek the Tatman formation is sandstone and carbonaceous shale 50 to 150 feet thick. Elsewhere beds below the breccia are hidden by vegetation and colluvium.

Early Basic Breccia.—The Absaroka volcanic rocks above the Tatman and Willwood formations were considered to be Early Acid Breccia (Hewett, 1920, p. 545), on the basis of Knowlton's identification of "Fort Union" leaves from tuff in the lower part of the volcanic series. At the time the Early Acid Breccia was the only Yellowstone Park volcanic unit known to be as old as Paleocene or Eocene; the Early Basic Breccia was thought to be Miocene. Since then, Dorf (1939) has shown that the Early Basic Breccia flora is Middle Eocene and has also declared (personal communication) that Hewett's leaves are not diagnostic for they could have come either from the Early Basic Breccia or the Early Acid Breccia floras. Moreover, there is no Early Acid Breccia equivalent near the head of the Middle Fork of Owl Creek, south of Anchor, Wyoming, where Hewett found some of the leaves. The lowest volcanic unit in the area is the Tepee Trail formation (Love, 1939, p. 73) which Love correlates with the Early Basic Breccia.

On the basis of a mineralogical analysis, Pierce and Andrews (1941, p. 140) have called the volcanic rocks along the southwestern border of the Big Horn Basin the Early Basic Breccia. This correlation is confirmed by Rouse's identification (personal communication) of the Early Basic Breccia in the vicinity of the Greybull River and by the presence of basic breccia on Squaw Buttes.

DISCUSSION

Rocks recording the early Cenozoic history of the Absaroka Plateau are well exposed east of the Yellowstone National Park and at the southern margin of the Absaroka Range in the Wind River Basin. In the vicinity of the South and North forks of the Shoshone River and along the eastern flank of the Absarokas north of the Greybull River red-banded Willwood strata (Early Eocene) are overlain by the Early Basic Breccia of early Middle Eocene age. The Early Acid Breccia found locally between the Willwood and the Early Basic Breccia appears to be stratigraphically associated with the Willwood. The same sequence also occurs along the southwesern border of the Big Horn Basin, except that south of Grass Creek the Tatman formation lies between the Willwood and the Early Basic Breccia. In the southern foothills of the Absarokas there is a similar succession of strata. The variegated Aycross formation of Middle Eocene age is correlated by Love (1939, p. 66) with the Early Acid Breccia which yields an Early Eocene flora (Dorf, 1939). This correlation calls to mind the closely related Willwood and Early Acid Breccia in the South Fork region. Above the Aycross is the Tepee Trail formation, mineralogically equivalent to the Early Basic Breccia, but of Late Eocene age (Love, 1939, p. 73).

The reason for this discrepancy in age between supposedly equivalent stratigraphic units in the northern and southern Absarokas is not clear. Mineralogical analyses may be misleading, or the fossils inadequate to date the units accurately. Assuming the correlations are correct, the following may be the relationship between deposition in the two areas. The breccias must have accumulated earlier in the North, nearer the volcanic source. The Early Acid Breccia was the first deposited. Material eroded from it supplied, in part at least, the Middle Eocene Aycross sediments. While the Aycross was being deposited to the south the Early Basic Breccia began to accumulate in the northern Absaroka region. More reworked material, together with further deposition of basic breccia, produced the Late Eocene Tepee Trail formation in which an abundance of well-bedded tuff and shale contrasts markedly with the preponderance of coarse sediments in the Early Basic Breccia. In the northern Absarokas the Early Basic Breccia attains a thickness of 5500 feet, and in it are buried 15 successive "fossil forests", suggesting a long period of accumulation. It is possible, then, that deposition of the basic breccia in the north began in the Middle Eocene and continued into Late Eocene time.

SOUTH FORK AND NORTH FORK REGIONS

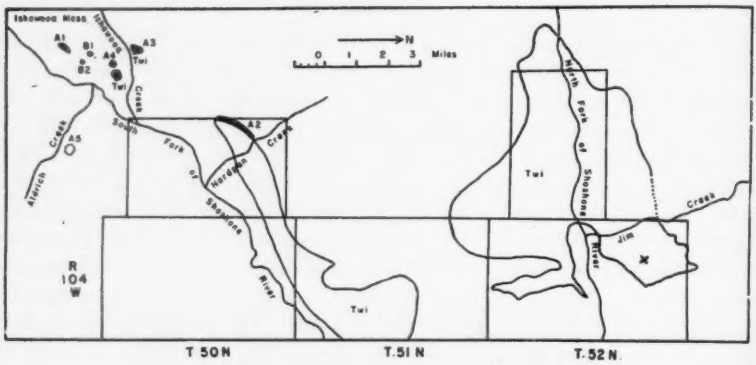
SOUTH FORK REGION

Willwood formation.—The relationship of the Willwood formation to the volcanic rocks of the Absaroka Range is of great importance in determining the early Cenozoic history of this portion of the Rocky Mountains.

The Willwood formation (Fig. 3, Twi) is well exposed on the north side of the South Fork of the Shoshone River in an outcrop 10 miles long, where it consists of massive

yellow sandstone and red-banded shale. Mammal fossils from the Willwood along the North Fork establish its age as Early Eocene—Gray Bull through Lost Cabin (Jepsen, 1939).

In most places Willwood strata are nonconformable on upturned Mesozoic rocks. Pierce (1941, p. 2039–2040) believes that thrusting occurred in this region during


Ishawooa Mesa
Ishawooa Creek
A1
B1
B2
A4
A3
Twi
A2
A5
Twi
Twi
Twi

the rock were examined by Dr. H. H. Hess (Demarest, 1940, p. 33) who stated that they are definitely acid. Further evidence favoring this correlation is the fact that the tuff lies beneath the Early Basic Breccia.

In the scarp north of Ishawooa Creek (A3) the tuffaceous facies of the Early Acid Breccia and Willwood strata dip steeply northward as a result of faulting. Above an angular unconformity truncating the faulted Willwood and acid tuff is a tuffaceous facies of the Early Basic Breccia.

Mammal teeth were found in the Early Acid Breccia at the northeast end of Ishawooa Mesa (A4). Dr. G. L. Jepsen has prepared the following report on the fossils. A well-preserved first or second lower molar of *Hyopsodus* has a small metastylid on the posterointernal slope of the metaconid. This is a common feature in Bridger species, such as *H. paulus*, and is rare in Early Eocene species. No Gray Bull species shows the cusp, and only 1 individual in 20 from the Lysite or Lost Cabin shows it. Fragmentary titanothere teeth suggest a post-Lost Cabin age.

In the landslide debris on the north bank of Aldrich Creek Early Acid Breccia (A5) is exposed. A stout incisor and an anterior lower left cheek tooth of a rodent collected in this locality are larger than any known rodent teeth from the Early Eocene. Jepsen (Demarest, 1940, p. 55) believes that these teeth are Lost Cabin or younger.

Fossil leaves from the Early Acid Breccia of Yellowstone Park are of Early Eocene age (Dorf, 1939, p. 1907).

Early Basic Breccia.—The thickest and most extensive volcanic rock in the Absaroka Range is the Early Basic Breccia. In the South Fork region the lower 400 to 900 feet comprises drab tuff beds and sandstone. Such tuff units are developed locally, probably resulting from a pause in volcanic activity long enough to allow some deformation and erosion before the coarse breccia was erupted (Rouse, 1937, p. 1266). It is of great importance to the problem of dating the Absaroka volcanic rocks that Rouse has concluded that his "early basic tuffs" are part of the Early Basic Breccia.

Near the base of this section of tuff, a mile north of Merrill Snyder's ranch (B2) Demarest collected several plant fossils. Dorf examined the specimens, which include *Acrostichum hesperium*, *Dryopteris weedi*, and *Equisetum sp*, and found (Demarest, 1940, p. 58) that the assemblage is equivalent to a flora from the basal tuff of the Early Basic Breccia near Valley, Wyoming. Examination of the Valley flora had convinced Dorf (1939) that it is closely related to the floras of the Early Basic Breccia of Yellowstone Park, the Aycross formation in the southern Absarokas, and the upper Green River formation near Green River, Wyoming, and that the Early Basic Breccia is Middle Eocene (Bridgerian). This conclusion accords with the suggested Eocene age of the Early Basic Breccia based on a study of the geologic history of the Grand Canyon of the Yellowstone River (Jones and Field, 1929, p. 273).

About 500 feet above the leaf-bearing beds (B2), a few mammal teeth were found in a fine-grained, shaly sandstone in the basic tuff (B1). Above and below this layer are massive sandstone beds. Of the five teeth that were collected, two suggest either Lost Cabin or Bridger age (Jepsen, 1939). One is the first right upper molar of *Microsyops*, a Bridger genus closely related to *Cynodontomys* from the Early Eocene.

The second is the last left upper molar of *Didymictis*, a Torrejon to Lost Cabin genus whose species become progressively larger during the Early Eocene. This specimen is larger than any yet found in the Lost Cabin. The other teeth are not diagnostic.

The later volcanic rocks of the Absaroka Range are not involved in the present problem of correlating Eocene events. It should be noted, however, that before the extrusion of the Early Basalt Sheets the Early Basic Breccia was tilted in places to 35° (Rouse, 1937, p. 1290).

NORTH FORK REGION

The Willwood formation in the North Fork region (Fig. 3, Twi) crops out beneath the Early Basic Breccia and over most of the area lies unconformably on the Cody shale (Stevens, 1938, p. 1243–1244). Its massive yellow sandstone and variegated shale resemble Willwood sediments high on McCulloch Peaks.

In the excellent exposure east of Jim Creek (Fig. 3, X) 1000 to 1200 feet of Willwood strata lie on the Cody shale and are capped by 1800 feet of Early Basic Breccia (Rouse, 1937, p. 1267). Mammal fossils from the Willwood show the beds to be Gray Bull and Lost Cabin (Jepsen, 1939, p. 1914). *Homogalax*, diagnostic of Gray Bull beds, was found in the upper part of a massive yellow sandstone about 250 feet above the base of the formation, while an assemblage of fossils including the Lost Cabin genus, *Lambdotherium*, was collected from a somber layer in the variegated shale approximately 225 feet above the *Homogalax* horizon.

The Early Basic Breccia rests on a rugged surface cut in Willwood deposits near Jim Creek. To the east, however, the entire Willwood section is missing, and the breccia lies on the Cody shale, thereby demonstrating that after Willwood deposition erosion produced a topographic relief of 1000 feet or more. There is also considerable relief below the Early Basic Breccia in the Carter Mountain and Meeteetse Mountain areas (Stevens, 1938, p. 1258).

The great limestone block of Sheep Mountain rests on a surface cut across both the Willwood and the Cody, and its western end is covered by the Early Basic Breccia. A dike of breccia transecting the limestone (Rouse, 1937, p. 1278–1279) reveals that here the Early Basic Breccia was deposited after the emplacement of the block.

At the western edge of Sheep Mountain there are many isolated limestone blocks, some of them up to 500 feet in diameter. A few rest on surficially distorted Willwood, others are in the breccia a short distance above the Willwood-Early Basic Breccia contact. Stevens believes (1938, p. 1253) that the coincidence of the blocks with the higher parts of the pre-breccia topography developed in the Willwood indicates that the limestone capped the hills of Willwood before the deposition of the Early Basic Breccia.

SUMMARY

The following summary of the geologic history of the South Fork and North Fork regions was prepared before Pierce (1941, p. 2045) published his interpretation. The similar conclusions of these independent studies show that the early Cenozoic history of this area is now well established.

(1) There are no Lance or "Fort Union" equivalents west of Rattlesnake Mountain. It is not yet known whether these units were once present and later eroded

before deposition of the Willwood or whether, after accumulation of the Cody shale, the land was continuously eroded until the time of Willwood deposition.

(2) Diastrophism. During a long period of pre-Willwood orogeny Laramide structures were intensely deformed. The South Fork region was dislocated, and Rattlesnake Mountain was folded.

(3) Erosion. The Beartooth Mountains, Rattlesnake Mountain, and other Laramide structures were eroded as they were uplifted.

(4) Deposition. Willwood sediments were deposited on beveled Mesozoic strata. They may, perhaps, have spread across Rattlesnake Mountain.

(5) Deposition. Locally, the Early Acid Breccia accumulated conformably on the Willwood. Pre-Cambrian rocks were exposed in the uplands during Willwood time, hence the Early Acid Breccia lies on rocks as old as pre-Cambrian (Rouse, 1927, p. 1283) where Willwood strata are absent. Fossil plants from the Early Acid Breccia are of Early Eocene age; fossil mammals are late Early or early Middle Eocene.

(6) Erosion. At least locally a surface was cut across Willwood and Cody deposits.

(7) Diastrophism. The limestone blocks of the Heart Mountain "thrust" were moved into place on a surface which may have had some relief for all the blocks are not at the same elevation. The Willwood and Early Acid Breccia were faulted and folded.

(8) Erosion. The pre-thrust surface was deeply dissected.

(9) Deposition. Early Basic Breccia spread across a surface of considerable relief and buried some of the limestone blocks. According to the plant fossils the Early Basic Breccia is Middle Eocene, according to the mammalian fauna it is Lost Cabin or early Bridgerian. Its stratigraphic position above Lost Cabin beds of the Willwood formation makes it post-Lost Cabin.

(10) Diastrophism. The Early Basic Breccia was tilted and eroded before extrusion of the Early Basalt sheets.

RÉSUMÉ OF LATE CRETACEOUS AND EARLY CENOZOIC HISTORY OF THE BIG HORN BASIN REGION

CRETACEOUS PERIOD

Intermittently during the Cretaceous sandstone tongues, often perhaps in the form of great deltas, spread eastward across the Rocky Mountain geosyncline. As vast lowland swamps slowly displaced the sea in late Cretaceous time the Mesaverde sandstone facies accumulating in western Colorado extended into northwestern Wyoming. The Mesaverde formation in the Big Horn Basin is the oldest of a series of continental deposits in which folding and unconformities reveal that compression of the basin sediments recurred during late Cretaceous, Paleocene, and Eocene time. In this interval of intense Laramide orogeny the bordering mountain structures were differentially elevated and deeply eroded; the basin floor was depressed. Yet no lofty mountains rose above the basin for erosion, with attendant aggradation of the basin, maintained mature topography. The great thickness of waste-fill accumulated in a warm-temperate lowland.

The Mesaverde deposits comprise 1000 to 1500 feet of thick buff sandstone beds. Coal is abundant in the lower portion. On the southwest side of the basin, where

evidence of the last marine deposition is found in a thin bed of shale above the lowest coal, the Mesaverde is probably equivalent to the Telegraph Creek, Eagle, Claggett, and Judith River formations in central Montana; in the east it correlates only with the Judith River and possibly the Claggett, for characteristic Eagle fossils occur in the underlying Cody shale.

Soft brown and gray continental shale and sandstone, 1400 feet thick, were deposited conformably on the Mesaverde while the sea returned to the area north, east, and south of the basin, suggesting that at this time the Big Horn Basin was deformed as an independent structural unit. Bentonite beds in these Meeteetse sediments, as well as in many other Cretaceous formations, evidence recurring volcanic activity in the uplands. When continental conditions again encroached upon the seaway in central Montana the final retreat of the sea was marked by a regressive marine sandstone, locally named Lennep, Horsethief, and Fox Hills. In the Wind River Basin the marine Lewis shale and Fox Hills formation between the non-marine Mesaverde and Lance, indicate that here, as in central Montana, marine conditions prevailed while the continental Meeteetse deposits accumulated in the Big Horn Basin.

The extensive Lance formation above the Meeteetse and Fox Hills is composed of 1000 to 1800 feet of massive, poorly indurated buff sandstone and subordinate drab shale deposited in a swamp and flood-plain environment.

Both faunal and floral data show clearly that the Mesozoic-Cenozoic boundary is between the Lance and overlying Paleocene strata.

PALEOCENE EPOCH

Drab Paleocene shale and sandstone, 3500 feet thick in the northwestern part of the basin, accumulated in a lowland environment that was a continuance of antecedent Cretaceous conditions. In the border belt the sediments spread across truncated folds, but unconformities near the margin of the basin do not indicate the position of the Mesozoic-Cenozoic boundary, because conformable strata were deposited in the middle of the basin in late Cretaceous, Paleocene, and Eocene time.

EOCENE EPOCH

The unheralded appearance of the Artiodactyla, Perissodactyla, the Adapidae, and Hyaenodontidae marks the beginning of Eocene time. Nearly coincident with the introduction of this fauna into the Big Horn Basin region, red-banded Willwood deposits began to accumulate on flood plains and in river channels, while ash spread from volcanoes in the surrounding ranges. Significant Laramide deformation had occurred before Willwood sediments accumulated. As a consequence the Willwood was locally deposited on folded late Cretaceous and Paleocene strata and on the beveled edge of the monocline flanking the mountain rim. Post-Willwood movement, perhaps that late phase of the Laramide revolution that elevated the Rocky Mountain region, affected pre-existing folds and locally arched the Willwood.

In Middle Eocene time crustal downwarp formed a lake basin in which Tatman deposits accumulated conformably on the Willwood under conditions very similar to those that produced the shore facies of the Green River formation. The basin floor probably was no more than 1000 feet above sea level, and the near-by mountains

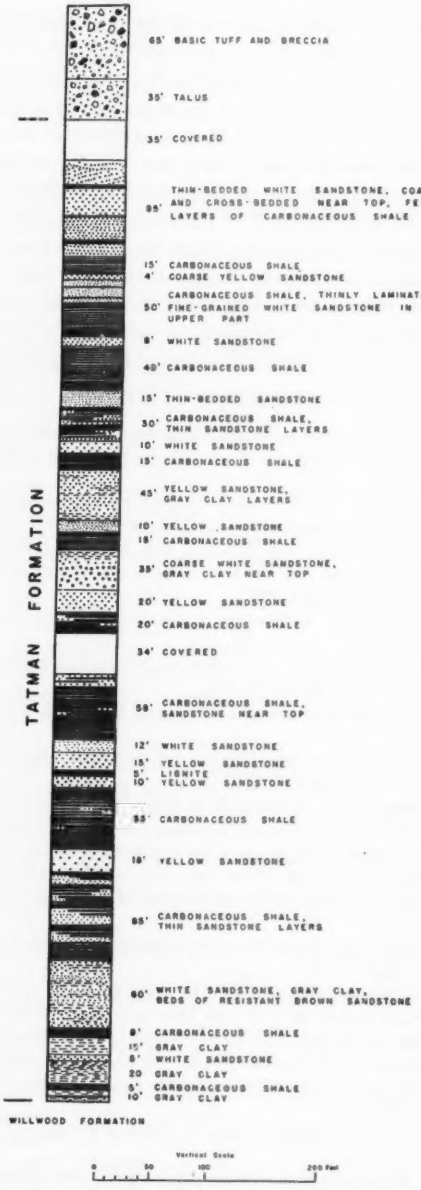

65' BASIC TUFF AND BRECCIA
35' TALUS
35' COVERED
85' THIN-BEDDED WHITE SANDSTONE, COARSE AND CROSS-BEDDED NEAR TOP, FEW LAYERS OF CARBONACEOUS SHALE
15' CARBONACEOUS SHALE
4' COARSE YELLOW SANDSTONE
50' CARBONACEOUS SHALE, THINLY LAMINATED, FINE-GRAINED WHITE SANDSTONE IN UPPER PART
8' WHITE SANDSTONE
40' CARBONACEOUS SHALE
15' THIN-BEDDED SANDSTONE
30' CARBONACEOUS SHALE, THIN SANDSTONE LAYERS
10' WHITE SANDSTONE
15' CARBONACEOUS SHALE
45' YELLOW SANDSTONE, GRAY CLAY LAYERS
10' YELLOW SANDSTONE
18' CARBONACEOUS SHALE
35' COARSE WHITE SANDSTONE, GRAY CLAY NEAR TOP
20' YELLOW SANDSTONE
20' CARBONACEOUS SHALE
34' COVERED
59' CARBONACEOUS SHALE, SANDSTONE NEAR TOP
12' WHITE SANDSTONE
15' YELLOW SANDSTONE
5' LIGNITE
10' YELLOW SANDSTONE
35' CARBONACEOUS SHALE
18' YELLOW SANDSTONE
85' CARBONACEOUS SHALE, THIN SANDSTONE LAYERS
60' WHITE SANDSTONE, GRAY CLAY, BEDS OF RESISTANT BROWN SANDSTONE
8' CARBONACEOUS SHALE
15' GRAY CLAY
6' WHITE SANDSTONE
20 GRAY CLAY
5' CARBONACEOUS SHALE
10' GRAY CLAY
TATMAN FORMATION
WILLWOOD FORMATION
Vertical Scale
0 50 100 200 Feet

FIGURE 4.—*Stratigraphic section of the Tatman formation*

From the base in sec. 2, T.48 N., R.98 W., to the top of Squaw Buttes

were low. Later in Middle Eocene time the Early Basic Breccia encroached upon the area, interrupting deposition of the Tatman sediments.

Sometime in the rather brief interval between the end of Willwood deposition and eruption of the Early Basic Breccia, or perhaps associated with the spread of the breccia, the limestone blocks of the Heart Mountain "thrust" were moved into place on Heart Mountain, McCulloch Peaks, and in many localities west of Rattlesnake Mountain. The accumulation of several thousand feet of Absaroka volcanic rocks, together with progressive regional uplift of the Rocky Mountains during later Cenozoic time, inaugurated in the basin a new cycle of degradation and a change from early Cenozoic humid conditions to the later semiarid climate. Not until this time was there great topographic relief. As excavation of the basin-fill progressed, the consequent drainage system that had developed on the surface of the early Cenozoic sediments became superposed on older structures at the border of the basin.

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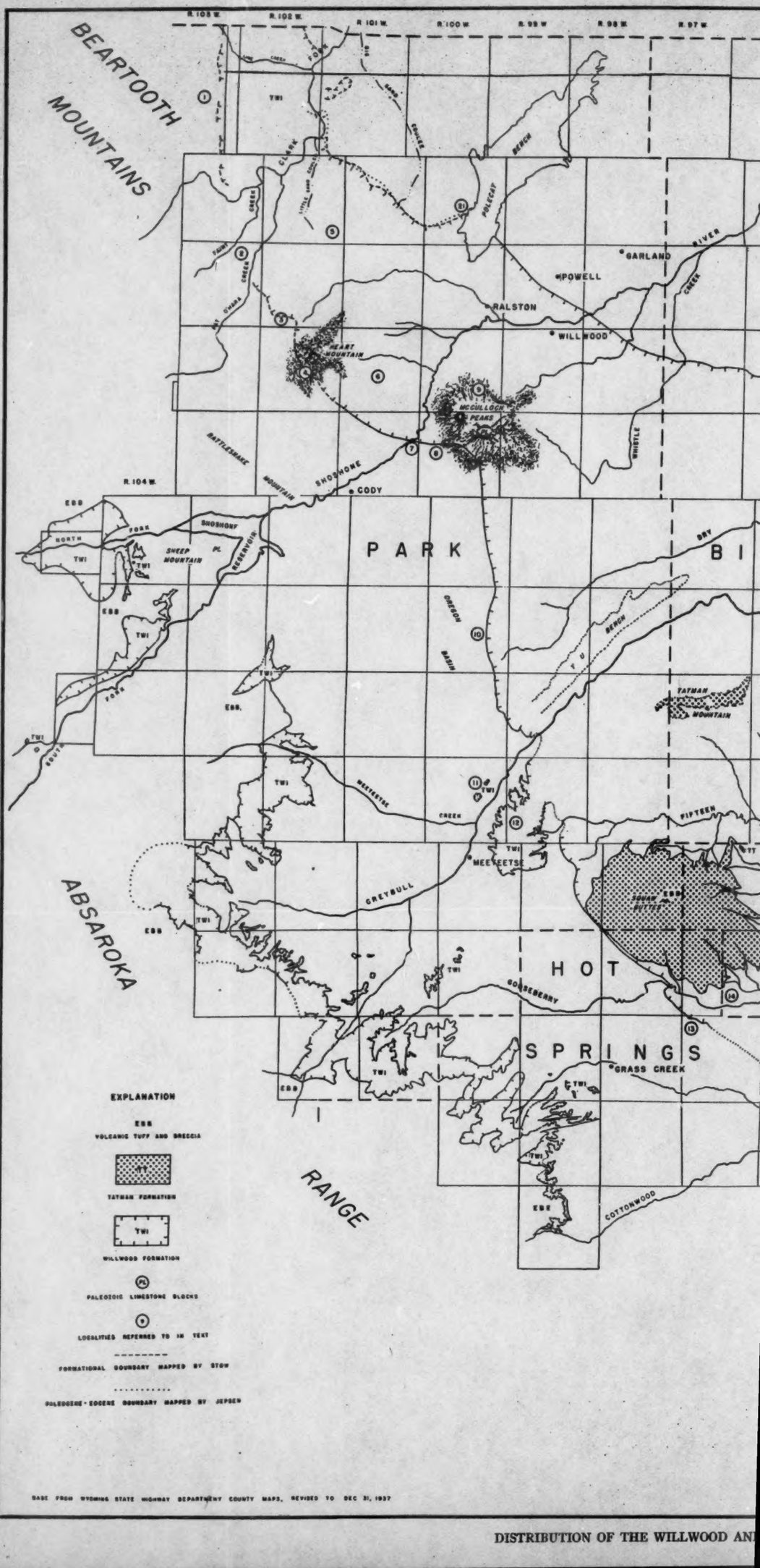

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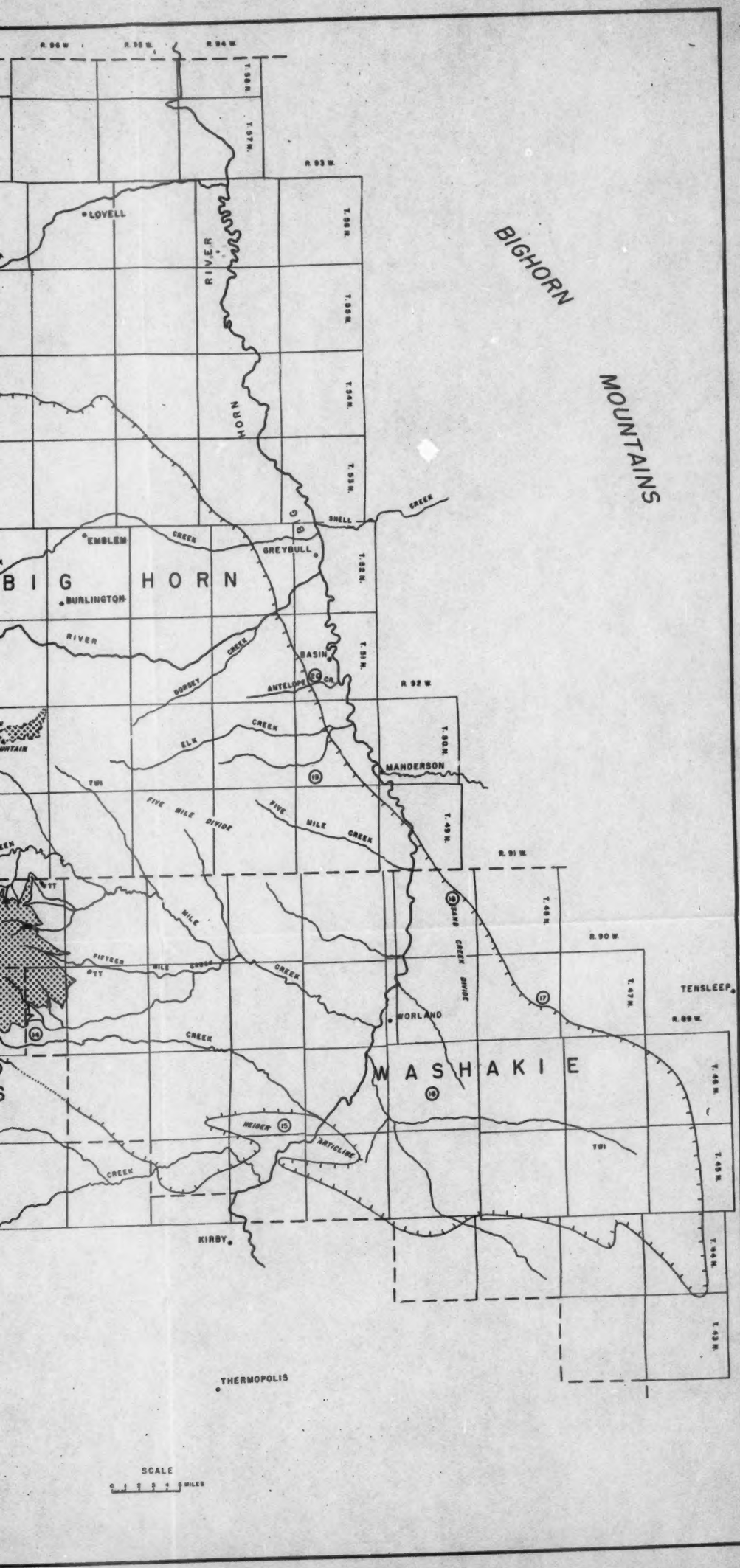

LWOOD AND TATMAN FORMATIONS

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SPECIFIC DATA ON THE SO-CALLED "READING OVERTHRUST"

BY BENJAMIN L. MILLER

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ABSTRACT

The article brings together several types of field evidence that seem to be inconsistent with the proposed "Reading Overthrust." Specific data are presented and discussed. Fortunately several valuable drill records have been secured and are offered. Intermontane valleys of erosion are shown

to be due to local structures and are not windows in an overthrust sheet. Occurrences of jasper are described and shown to occupy a definite stratigraphic position in the geologic sequence and are not the product of silicification along the sole of a great thrust. Gravimetric data are evaluated. Several localities are considered where existing conditions are either in disagreement with the overthrust idea or call for unusual coincidence.

INTRODUCTION

Extending from a short distance west of Reading northeastward to the Delaware River and continuous with the Highlands of New Jersey and New York there is a belt of hills and ridges of crystalline pre-Cambrian rocks (Fig. 1) variously called South Mountain, the Durham and Reading Hills, the Reading-Boyertown Hills, the Reading Hills, the Reading Prong of the New England Upland. They lie between the Great Valley of Cambrian and Ordovician limestones on the north and the Triassic sediments on the south. The belt is interrupted by intermontane valleys, mainly floored by Paleozoic limestones, some isolated but others connected with the Great Valley. In general, the rocks of this region are similar to those of the Philadelphia area, on the south side of the Triassic basin, in that they are highly metamorphosed rocks of both igneous and sedimentary origin.

This belt of crystalline rocks is conspicuous because they form hills, which in several places rise more than 1000 feet above sea level, whereas the near-by limestone valleys are rarely more than 400 feet. Most of the hills are wooded.

Geologists of both the First and the Second Geological Surveys of Pennsylvania recognized the greater age of these crystalline rocks and found evidence of this by the relationship with the less metamorphosed lower Paleozoic sediments resting upon them. Apparently all these attributed the present distribution and topographic features of the crystalline rocks to Appalachian (and possibly Taconic) orogeny with folding as the principal factor but recognized the existence of normal faults, reverse faults, and overturned folds. In some localities these have produced extremely complex conditions.

At the meeting of The Geological Society of America on December 29, 1934, Stose and Jonas (1935a) proposed a new structural interpretation with the claim that it more accurately explained the existing distribution of the pre-Cambrian crystalline rocks and Hardyston quartzite and the younger Paleozoic sedimentaries. Their hypothesis assumes that much of the crystalline rock and Hardyston mass is a great overthrust sheet that is designated as the Reading Overthrust. This great overthrust is believed to be the dominant structural feature of the region.

The present paper is concerned with the examination of field evidence with an attempt to decide which one of these divergent interpretations seems to be in more agreement with known data. The writer concludes that the overthrust hypothesis is not supported by the evidence, so that most of this contribution is devoted to specific occurrences that seem to controvert the overthrust interpretation.

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FIGURE 1.—*Generalized map of the pre-Cambrian crystalline rocks of the Reading prong of the New England Uplands*

Taken from the Geological Map of Pennsylvania (1935). Some small areas of Paleozoic sedimentary rocks are included. Scale: 1 inch = 10 miles.

and B. Willard have read and criticized the manuscript. E. A. Brown, J. J. Matsko, E. K. Mulhausen, and H. Wilkens have ably assisted in the field studies. Especial thanks are offered to J. B. Hersey for gravimetric data which he generously contributed.

RÉSUMÉ OF PUBLISHED ARTICLES ON THE "READING OVERTHRUST"

The general conclusions of the initial paper by Stose and Jonas (1935a) are fairly well stated in the two following quotations.

"Most of the mountain area is a great overthrust sheet composed of pre-Cambrian rocks and Hardyston quartzite, dissected and cut through by the deeper drainage, exposing the overridden Paleozoic limestones." (p. 762)

"Most of the mountain area from its end southwest of Wernersville to South Mountain south of Emaus [Emmaus], a distance of over 50 miles, and probably its extension across Pennsylvania to Easton, is believed by the writers to be part of a great overthrust sheet which has ridden northwestward on a flat fault plane in the crystalline core of the mountains over lower Paleozoic rocks. . . . The overridden limestones, shale and quartzite are now exposed as windows, by erosion of the thrust sheet, in Oley Valley and in many other mountain valleys, and they also form the Great Valley north of the overthrust mass. In other words, the older rocks of most of the mountain area do not pass under the younger valley rocks in a normal folded sequence but overlie them in a tectonic series in which the position of the members is due to overthrusting." (p. 763–764)

The evidence presented was grouped under the headings of "Stratigraphic and Structural Discordance," "Mylonite on Thrust Plane," "Detailed Masses of the Overthrust Sheet" and "Valley Windows of the Overthrust Sheet."

Miller and Fraser (1935) objected to the "overthrust" hypothesis and presented eight examples of adverse evidence. Some of these were discussed in the reply by Stose and Jonas (1935b).

Fraser (1938) continued the discussion and described his investigations in a limited portion of the area. He summarized his conclusions with the following statement

"The writer believes that the structures found in the Reading Hills are not satisfactorily explained by introducing a great overthrust fault underlying these hills. On the contrary, it is believed the folds and faults produced at the time of Appalachian orogeny might well account for the present occurrences of many of the belts of limestone and quartzite found within the pre-Cambrian area. It is further believed that later normal faulting, resulting in the down-dropping of certain areas, has been the cause of some of these belts. The writer recognizes high angle thrust and normal faulting and folding as the dominant causes of the present areal distribution of formations in the Reading Hills." (p. 1211)

Stose and Jonas (1939) correctly called attention to an error in Fraser's map and further stated that they did not

"regard as adequate his explanation that the discordant relation of the rocks of mountain and of valley areas is due to Appalachian folding accompanied by thrust faults of local extent modified by later normal faulting and erosion." (p. 286)

They erroneously state that they "replied to each of the objections that Miller and Fraser had presented under 8 headings" (p. 281) in a discussion of their original paper.

At the 1940 winter meeting of the American Association for the Advancement of Science Stose and Stose presented a paper entitled *Further evidence of the Reading Overthrust* which has not been published, and their geologic map exhibited by lantern slide has not been made available. A brief abstract (Stose and Stose, 1940) states that further investigations have extended the overthrust interpretation

"eastward into the Allentown quadrangle. . . . The gravity determinations across the region show a marked gravity depression which does not support the interpretation that the pre-Cambrian rocks of the mountains are rooted in the crystalline basement and favor the overthrust theory." (p. 2007)

GENERALIZED STATEMENTS

So far as is known, the geologists who worked in the region prior to the proposal of the overthrust interpretation believed that the pre-Cambrian gneisses and schists of the Reading Hills everywhere underlie the Paleozoic sediments and that the exposed crystallines are in turn underlain by other ancient rocks not exposed.

It was, therefore, decidedly stimulating to have Stose and Jonas propose the overthrust hypothesis and draw sections showing most of the hills of pre-Cambrian rocks resting on overridden younger rocks, mainly Cambrian limestones, with the intermontane valleys designated as "windows." To the writer it was a challenge and called for a careful re-examination of the field evidence. It was somewhat disconcerting to be told that the hills of crystalline rocks had their origin elsewhere and had been broken from their moorings 15 to 25 miles to the southeast and pushed over more recent rocks until they came to rest in the places where they are now found. One area, Irish Mountain, was said to be in place. The overthrust block had split when this stationary block was encountered, and the two portions moved by on either side in a pincerlike manner.

The most extraordinary feature of the overthrust hypothesis is the juxtaposition of similar rocks of the transported and the stationary blocks. Although originally widely separated, the moving block came to rest in such a position that rocks of the same type in the two blocks are now in contact and possess similar structures.

The "Reading Overthrust," if it exists, is of major importance in Appalachian structure and deserves studied consideration. The problem will not be solved by dogmatic assertions or by generalized descriptions or arguments. Specific and exact data must either establish or disprove the existence of the proposed extensive overthrusting. The Stose-Jonas articles consist of maps, sections, and generalized and positive assertions but unfortunately lack descriptions of specific localities where the relationships described can be seen. The writer, therefore, here attempts to bring together various observations which have been made during many years of residence in the region and which may be of value in reaching a decision. Part of this evidence has been briefly presented previously, but it seems necessary to incorporate part of this with additional observations in order to present a complete picture of the situation. An especial effort is made to present specific evidence in order that future investigators can visit the localities and examine the various phenomena described.

STRATIGRAPHIC COLUMN

The formations involved in the "Reading Overthrust," as described by Stose and Jonas, range from the pre-Cambrian to the Upper Ordovician, inclusive.

Ordovocian	Martinsburg shale Leesport limestone Beekmantown limestone
Cambrian	Upper. Conocheague limestone Middle and Upper. Elbrook limestone Lower. Tomstown dolomite Hardyston quartzite[1]

[1] Note: In this article and elsewhere in the literature, "Hardyston quartzite" and "Hardyston sandstone" are used interchangeably because in some localities the sandstones have been metamorphosed to true quartzite.

pre-Cambrian	Dikes of diabase and pegmatite Pochuck gabbro gneiss Losee diorite gneiss Byram granite gneiss Pickering graphite gneiss

All these formations presumably are present in the overridden (autochthonous) block and were originally also represented in the "overthrust" (allochthonous) sheet. Erosion is supposed to have removed all the strata above the Lower Cambrian in the transported block so that it now contains only the pre-Cambrian crystallines and the Hardyston and Tomstown strata. The maps presented by Stose and Jonas do not differentiate the various divisions of the pre-Cambrian, and the Martinsburg and Leesport are grouped together.

MAPPING DIFFICULTIES

Anyone who has had field experience in southeastern Pennsylvania or similar regions of complex structure and inadequate exposures fully realizes that many geologic formation boundaries must be mapped with insufficient data. Therefore no two geologists working independently could be expected to present identical maps. In fact, the known data in places may result in maps of fairly wide divergence. Where the rocks are as badly folded and faulted as in the Reading Hills region the geologist must draw formation lines in many places on the basis of his own conception of the general structure. He must, however, always keep in mind that lines thus drawn should never in turn be accepted as evidence of his structural interpretation.

RECORDS OF DRILLING

GENERAL CONSIDERATIONS

The following quotation of Stose and Jonas (1935, p. 776–777) prompted the search for records of deep drilling in the region:

"Structure sections drawn across the Reading and Boyertown Hills are presented in Figures 7 and 8, and clearly show the thinness of the overthrust plate, largely composed of pre-Cambrian rocks, which is cut through by numerous valley windows, exposing overridden Cambrian limestones and quartzite."

The figures and descriptions given show the "overthrust plate" with a maximum thickness of about 700 feet but in most places less than half that amount. Along the edges it decreases to zero. The thickness can readily be determined inasmuch as the sole of the "overthrust" is represented as approximately the level of the overridden limestone valleys. Therefore, drilling started in the "overthrust plate" should encounter the underlying overridden rocks at moderate depths.

Miller and Fraser (1935, p. 2033–2034) cited several places where drilling in the "overthrust" should have encountered limestone of the overridden block and did not. In the reply of Stose and Jonas (1935, p. 2038) this evidence was dismissed with the statement that

"reports of drilling must, of course, be considered, but the depth of old drillings and their character, if information comes by word of mouth, is, at best, hearsay."

In addition to deep drilling, previously cited, which seems to disprove the overthrust hypothesis, the record of a recent deep drilling made specifically to test this

interpretation is also offered. It seems advisable to review and fully describe most of the reliable evidence known to the writer that bears directly on the problem inasmuch as supplementary information is presented in those cases where previous inadequate descriptions have been published.

EMMAUS BOROUGH WELL (ALLENTOWN QUADRANGLE)

In April 1909, the writer was called into conference by the members of the Emmaus Borough Council to advise them in regard to a well being drilled at a small reservoir on the slope of South Mountain east of the village (Fig. 1). The site is almost exactly on the Upper Milford-Salisbury township line, and about 15 feet from the road that leads over the mountain.

The location of the well is such that if the gneiss here is overthrust on Elbrook limestone, as claimed by Stose and Jonas, and shown on their maps, limestone should have been encountered beneath the hillside talus, and the remaining distance should have been drilled in Elbrook limestone. The site of the well is on the 600-foot contour almost exactly 200 feet above the comparatively flat limestone valley on which the Borough of Emmaus is built. Thus, the bottom of this 700-foot well is several hundred feet below the sole of the "overthrust" as described by Stose and Jonas.

There was no doubt that the hole was started in the Hardyston as prominent sandstone beds are well exposed above the reservoir, up the hill from the well, about 50 feet distant, and dipping steeply toward the well (Fig. 2). Also, at one time a small sandstone quarry was worked a short distance below the well. The Hardyston beds overlie the pre-Cambrian gneiss and dip to the northwest in the normal manner. The generalized map by the writer (1925) shows the Hardyston sandstone along the face of the mountain and the location and depth of the well. Reference is made to the well in the accompanying text (1925, p. 176, 183). Stose and Jonas refer to this publication but not to this locality.

Plate 52 in the Stose-Jonas original article shows South Mountain east of Emmaus composed of pre-Cambrian rocks. This map and Plate 53 show many areas of Hardyston quartzite, but none east of Emmaus. Plate 53 shows Elbrook limestone of the stationary block extending to the boundary of South Mountain of the "overthrust" block. This boundary marks the limit of pre-Cambrian rocks on Plate 52.

There is no near outcrop of limestone, but a well dug in the east part of the borough some years ago passed through a considerable thickness of rotten shaly limestone. The writer and E. T. Wherry examined the material at the time of digging and were convinced that it belonged to the Tomstown formation.

These facts indicate that here we have the normal structure of Hardyston overlying the pre-Cambrian gneiss and dipping toward the valley and disappearing beneath the Tomstown limestone as represented in Figure 2A. Thus "the evidence of stratigraphic and structural discordance of the rocks of the mountain area with the adjacent rocks of the valley," claimed by Stose and Jonas, does not seem to exist here.

Drilling of the Emmaus Borough well was in progress when the writer visited the place and inspected the drill cuttings which were unquestionably pre-Cambrian gneiss. After passing through a few feet of hillside wash and rotten rock, Hardyston

sandstone was encountered. The depth at which the drill passed from the Hardyston to the underlying gneiss was not determined. Drilling was stopped in gneiss at the depth of 700 feet on the advice of the writer, who pointed out the improbability of obtaining an adequate supply of water by deeper drilling.

This evidence is cited to show that both the normal order of formations, as shown by outcrops of rocks on the mountain slope, and the drill record furnish evidence to

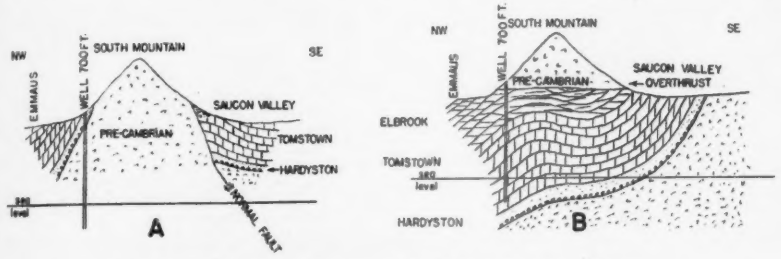


FIGURE 2.—*Structure sections through South Mountain east of Emmaus*

A. According to B. L. Miller. Note 700-foot well starting in Hardyston sandstone and ending in pre-Cambrian rocks. Absence of Hardyston at surface on southeast side is attributed to a normal fault. Limestone is not exposed but probably is Tomstown.

B. Hypothetical section, drawn by Miller, according to the "overthrust" hypothesis and to the Stose-Jonas maps (1935, Pls. 52, 53). These maps show pre-Cambrian in contact with Elbrook on the northwest and with Tomstown on the southeast side of the mountain. The 700-foot well should have been in limestone for almost the entire length as shown and not in Hardyston and pre-Cambrian as it actually is.

Vertical scale: 1 inch = 1000 feet. Horizontal scale: 1 inch = 2 miles.

controvert the overthrust explanation of South Mountain in the Emmaus region. The conditions as determined by the writer and as they might be on the basis of the "overthrust" hypothesis are shown in Figure 2.

SAUCON VALLEY NEAR FRIEDENSVILLE (ALLENTOWN QUADRANGLE)

In the original paper by Stose and Jonas (1935a, Pls. 52, 53) the western portion of the Saucon Valley in which Vera Cruz is situated is shown as a "window" in the "overthrust" sheet. In the oral presentation (Stose and Jonas, 1940) Stose exhibited a lantern-slide map showing the whole of Saucon Valley as a window. From an unexpected source evidence has recently been furnished to disprove this interpretation.

When the Friedensville zinc mines were worked during the latter half of the last century an enormous amount of ground water was encountered. At the time of operation and later there was considerable speculation as to the source of the water. Some persons seemed to think it was in excess of the amount of water falling as rain over the Saucon Valley area that would normally pass underground in the cavernous limestones. Being familiar with the "overthrust" interpretation of South Mountain the company geologist in charge of exploratory drilling operations during 1940–1941 looked about for another source for part of the water and concluded there was a possibility that some of it may have come from the Lehigh River that flows on the other side of the mountain about 2½ miles away. This might happen if, according to the "overthrust" hypothesis, the pre-Cambrian gneisses of South Mountain have been

thrust northward over the Paleozoic limestones, which would thus be continuous beneath the crystalline mountain mass.

Three diamond drill holes were put down (Fig. 3) to determine the source of the abundant water. The first hole was drilled vertically to the depth of 610.5 feet and

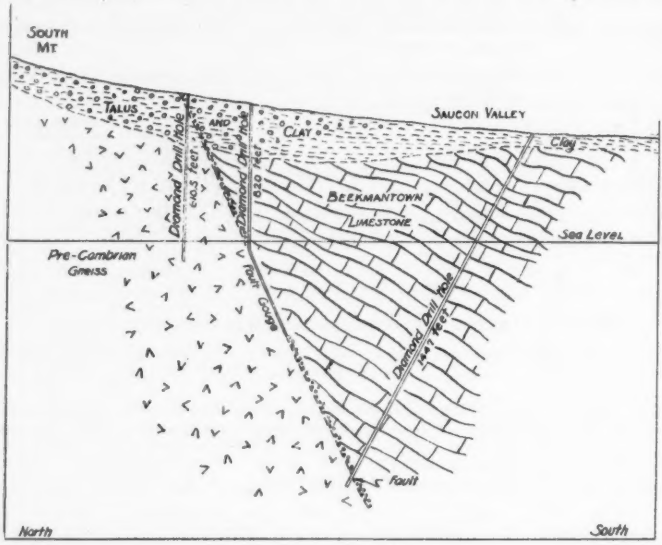


FIGURE 3.—*Section on south slope of South Mountain near Friedensville*

Showing contact of limestones of Saucon Valley and pre-Cambrian rocks of South Mountain, based on drill records. Disproves "overthrusting" of the pre-Cambrian rocks on Paleozoic limestones. Horizontal and vertical scale: 1 inch = 630± feet.

encountered only gneiss below the hillside talus. The second, also vertical, was drilled to a depth of 820 feet. After passing through the surficial clay it encountered Beekmantown limestone. At a little over 500 feet the gneiss was reached. The limestone-gneiss contact is a fault marked by broken rock and gouge, and the drill was deflected (Fig. 3). The third hole was drilled at an angle. It started in the Beekmantown limestone and ended in the gneiss at a distance of 1447 feet and over 1000 feet below the level of Saucon Valley. The two vertical holes are located on the lower slope of South Mountain half a mile northwest of the old Ueberroth zinc mine, on the north side of the highway. The inclined hole is due south, on the south side of the road.

The results, as shown on the section, seem to prove that, instead of being a "window" in an overthrust block, Saucon Valley is mainly the result of a normal fault of great displacement that has dropped the limestones of the valley to their present position, a view long held by the writer and his Lehigh University colleagues. The drilling clearly shows that South Mountain does not rest on Paleozoic limestones, and it is therefore inconceivable that water from the Lehigh passes under the mountain to the cavities of the Saucon Valley limestones. A displacement along the same

fault plane of approximately 4000 feet was calculated at a locality north of Lanark about 2 miles west of the place where the drilling was done. There the fault has brought Jacksonburg (Ordovician) cement rock in contact with the pre-Cambrian gneiss. Figure 4 shows the two different structural interpretations.

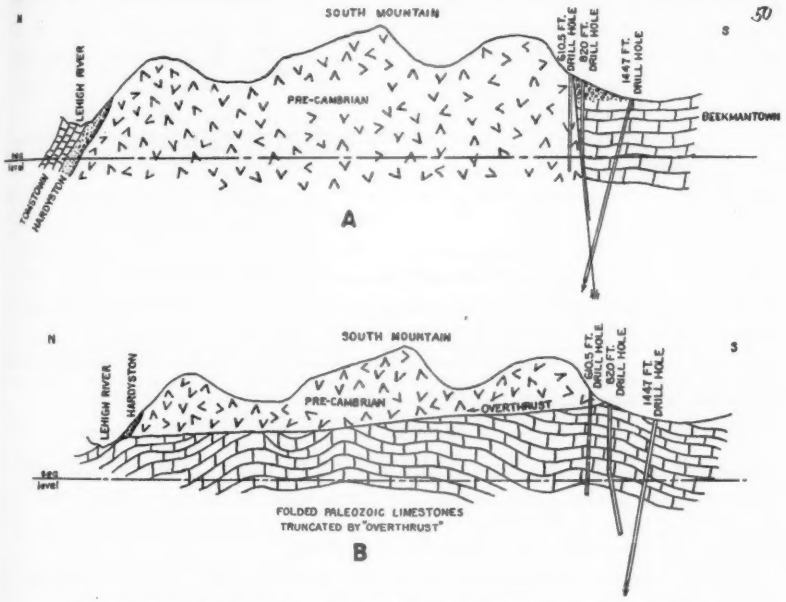


FIGURE 4.—*Structure sections through South Mountain near Friedensville*

A. According to B. L. Miller. On the north side of South Mountain the Hardyston is shown dipping normally beneath the Tomstown limestone. On the south side the Beekmantown limestone is in contact with the pre-Cambrian due to a normal fault. (*See* Figure 3.)

B. According to the "overthrust" hypothesis as interpreted by the writer. Uppermost drill hole should have encountered overridden Paleozoic limestone, and the other two should not have struck pre-Cambrian rocks. (*See* Figure 3.)

Vertical scale: 1 inch = 1000± feet. Horizontal scale: approximately 1 inch = 1 mile.

If South Mountain is eliminated as a part of the "overthrust" it is difficult to conceive how the gneiss hills to the southwest (Stose and Jonas, 1935a, Pls. 52, 53) can be overthrust. They are continuous with South Mountain, composed of the same kind of rocks, and are in conspicuous alignment.

SHENKEL HILL, EAST OF OLEY VALLEY (BOYERTOWN QUADRANGLE)

About 30 years ago the Berks County Development Company prospected for magnetite ore in the "overthrust block" east of the Oley Valley "window." They dug two shafts and put down 11 2-inch vertical diamond drill holes. The holes were drilled within a radius of about 1000 feet. The depths are as follows:

No.	Feet	No.	Feet	No.	Feet
1	1000	4	290	7	117
2	250	5	260	10	1200
3	246	6	266	11	748

They are located on the top of the hill, north side of the road, almost exactly ¾ mile west of Shanesville and a mile east of the edge of the "overthrust block" as shown by the Stose-Jonas maps (1935a, Pl. 52, 53).

The driller's records have been furnished the writer by Aubrey H. Weightman, one of the officials, with the exception of holes 8 and 9 which are missing. When the

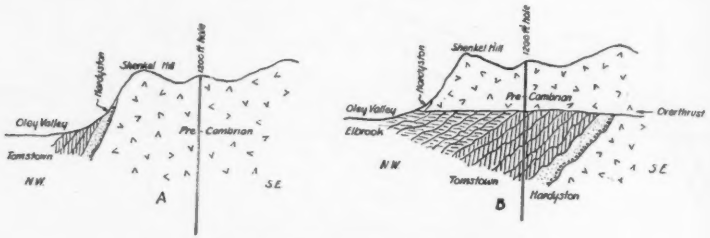


FIGURE 5.—*Structure sections through Shenkel Hill*

A. According to the writer. Hardyston dipping toward Oley Valley is believed to pass normally beneath Tomstown limestone. The 1200-foot exploratory drill hole was entirely in pre-Cambrian rocks.

B. According to the "overthrust" hypothesis. Is mainly an enlargement of a portion of the Stose-Jonas section (1935a, Fig. 7, p. 774). Hardyston is shown ending abruptly at the sole of the fault and not continuing beneath the limestone of the valley. Elbrook limestone is mapped in contact with the Hardyston. The 1200-foot hole should have been drilled mainly in the Paleozoic limestones and possibly some Hardyston, probably as shown.

Vertical scale: 1 inch = 1250± feet. Horizontal scale: 1 inch = 1¼ miles approximately.

writer and D. M. Fraser visited the locality in 1936 many of the cores were still in the core boxes. When again visited in 1941, accompanied by R. D. Butler, and later by G. H. Ashley, R. W. Stone, and S. H. Cathcart, the wooden core boxes had decayed, and the cores were lying about in heaps.

The cores were examined for limestone with extreme care. All the cores were of pre-Cambrian gneiss with some magnetite or, rarely, vein quartz.

The driller's records reveal his inability to classify properly the rocks penetrated, but this does not invalidate the conclusion that only pre-Cambrian crystalline rocks were encountered. There was evidently good core recovery inasmuch as no rotten or fragile material was seen, and some of the core sections were more than 4 feet in length. The drill records are not published, but copies are being sent to the office of the Pennsylvania Geological Survey for filing.

The structure sections (Fig. 5) have been constructed by the writer to present the two interpretations graphically.

The hill where the holes were drilled is between 780 and 800 feet above sea level. One mile west of Shenkel Hill the Stose-Jonas maps show limestone on the east side of the Oley Valley "window," at an elevation of 400 feet, and limestone in another isolated "window" 1 mile west of Hill Church and 1½ miles northeast of the site of the drilling at an elevation of 500 feet. Four miles to the east, between New Berlin and Bechtelsville, the "window" limestone is at 400 feet, and 3½ miles to the south it is at about the same elevation or possibly lower. From this evidence of "window" limestone to the west, northeast, east, and south at distances of 1 to 4 miles from the site of the drill holes and in conformity with the Stose-Jonas statement of a "flat fault plane" (p. 763), the deeper drill holes should have encountered Paleozoic lime-

stones at a depth of approximately 300 feet. This makes some allowance for the lowering of the limestones in the "windows" after the exposure of limestone by the removal of the overlying "overthrust sheet," as indicated by their cross section (Stose and Jonas, 1935a, p. 774, Fig. 7B). The lower 800 to 900 drill hole feet No. 10 should have been entirely in Paleozoic limestones. Similarly drill hole No. 1 should have been drilled 700 feet into the same limestones, and No. 11, 448 feet. Altogether approximately 2048 feet of core should be limestone, and 2329 feet pre-Cambrian rocks.

If one is inclined to discount the evidence presented because of the incorrect designation by the driller of the kinds of rocks penetrated, it may be well to recall that the prospect drilling was done for the location of magnetite ore which occurs only in the crystalline rocks of the region. Drilling would have been promptly discontinued if limestones had been encountered.

In addition, the driller would undoubtedly recognize limestone or, because it is much softer, would at least distinguish it from the rocks above. His records indicate hard rocks throughout. This, added to the absence of any limestone in the piles of cores, furnishes evidence that the crystalline rock masses of the region are in place and have not been transported here by overthrusting.

ANTIETAM COVE WELLS, ADJOINING CAPELLA HILL (ALSACE TOWNSHIP)

Three wells drilled in the edges of the "overthrust" sheet (Fig. 8) are described in the discussion of the Antietam Cove "window."

IRON ORE PROSPECT DRILLING, NEAR LOBACHSVILLE (PIKE TOWNSHIP)

About 1910 the Central Iron and Steel Co., Harrisburg, in prospecting for magnetite ore, put down two diamond drill holes in the southeast corner of the Jonathan F. Rohrbach farm 1½ miles northeast of Lobachsville, each about 220 feet in depth (Figs. 6, 7). One was 2 inches in diameter, the other 1½ inches. They were in gneiss throughout the depth drilled.

About ¼ mile to the northwest the Stose-Jonas maps show limestone in a "window" along Pine Creek about 80 feet lower than the surface at the site of the drilling. Similarly, a hypothetical "limestone window" along Manatawny Creek 1 mile southeast of the site has about the same elevation. According to the "overthrust" hypothesis, therefore, these two drill holes should have had the lower 140± feet in Paleozoic limestone.

SEISHOLTZVILLE

Stose and Jonas (1935, p. 772, Fig. 6) give a "detailed geological map of the Seisholtzville-Sigmund-Zionsville valley window" and show iron ore pits at "overthrust contact." No better locality could be found than this for a drill hole to test the overthrust hypothesis, and fortunately a 394-foot vertical diamond drill hole was put down here in October 1942 on the Gehman property about 1 mile east of Seisholtzville by the Bethlehem Steel Co. From the Stose-Jonas map it is not possible to determine how much higher the surface of the ground is above the border of the "window" at the site of the drilling but probably no more than 20 feet and certainly less than 40 feet.

The hole was started in pre-Cambrian granite gneiss which, according to the "overthrust hypothesis," constitutes a part of the overthrust sheet resting on Paleozoic limestones. In that case the drill should have struck the limestone between 20 and 40 feet. Actually the hole continued in the granite gneiss to a depth of 260 feet.

FIGURE 6.—*Pine Creek valley "window"*

From Stose-Jonas maps. Lower (western) portion is mapped Beekmantown, east of this a small patch of Conococheague, then Elbrook and in eastern portion Tomstown. All these limestones are supposed to be the "window" exposed by the wearing away of the pre-Cambrian and Hardyston of the "overthrust block." No limestones are exposed. Instead there is a fine exposure of gneiss where Elbrook limestone is mapped. (*See* Pl. 1, fig. 1.)

All but the lower portion of Pine Creek is cutting its channel in gneiss. (*See* Figure 7.) Scale: 1 inch = 1½ miles.

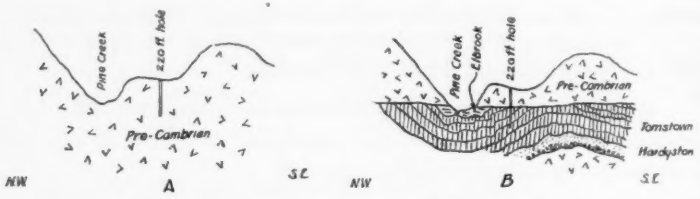


FIGURE 7.—*Structure sections across Pine Creek valley*

A. According to the writer. Only pre-Cambrian rocks are present throughout the 220-foot drill hole.

B. According to the "overthrust" hypothesis. Data for sketch taken from a portion of Stose-Jonas section (1935a, Fig. 8, p. 776). The 220-foot drill hole should have encountered Tomstown limestone.

Vertical scale: 1 inch = 1000± feet. Horizontal scale: 1 inch = 1 mile approximately.

From 260 to 394 feet the hole passed through a series of highly metamorphosed acid and basic rocks and calcareous rocks with streaks of magnetite at intervals. The microscopic examination of the calcareous rocks by D. M. Fraser indicates clearly that they too belong to the pre-Cambrian.

OTHER DRILL RECORDS

Miller and Fraser (1935, p. 2034) and Fraser (1938, p. 1207–1210) cite several other drillings that furnish similar evidence.

According to report, some of the shafts and drill holes of the magnetite ore workings in the Rittenhouse Gap region likewise extended well below the level of the "flat fault plane" without passing out of the pre-Cambrian rocks. Thus far, the writer has failed to verify these reports. It seems probable that dependable records of these and other magnetite ore mines that would be helpful in this investigation may be secured if careful systematic search is made. It is almost certain that additional important data secured in drilling for ore and water will be forthcoming from time to time.

SUMMARY OF DRILL RECORDS

The six drill records described furnish evidence of the pre-Cambrian rocks extending well below the level of the hypothetical fault plane of the "overthrust," as shown

in the Stose-Jonas sections. Further, no record has been obtained of any drilling that was started in these ancient rocks which passed through them into underlying (overridden) Paleozoic limestones. Stose and Jonas (1935a, p. 775) direct attention to their structural sections that "clearly show the thinness of the overthrust plate." It is believed that all the drill holes described should have passed through such an "overthrust plate." Any attempt to reconcile the data of the drill records to the "overthrust" hypothesis by subsequent folding of the fault plane is bound to lead to other major inconsistencies.

SO-CALLED "WINDOWS"

GENERAL STATEMENT

One of the major arguments for the "Reading Overthrust" is the presence of so-called "windows" of which about a dozen are shown on the Stose-Jonas maps (1935a, Pls. 52, 53; Fig. 6 and cross sections). (*See also* Plate 5 of this article).

These windows are of several shapes and sizes—long and narrow, long and broad, and small of irregular shape entirely surrounded by pre-Cambrian rocks. Saucon Valley is the largest, about 10 miles long and 5 miles wide. Oley Valley is almost as large.

All these "windows" are represented as floored by Cambrian and Ordovician limestones with a few patches of Martinsburg shale that have been exposed by the wearing away of the "overthrust" sheet.

If these so-called "windows" were such, there might be excellent reason for accepting the overthrust hypothesis. The pattern and the distribution of the various geological formations shown on the Stose-Jonas maps suggest such an interpretation. For that reason, special attention was given in the field to these areas to determine whether they are or are not "windows" of erosion in an "overthrust" block.

The writer has investigated all the important "windows" shown on the Stose-Jonas maps and has concluded that they are not "windows." He believes they are more rationally interpreted as blocks down-dropped by normal faulting and/or synclinal folds, or as simple erosion in gneiss areas. Some can be positively ruled out as windows, and in other cases the evidence is decidedly contrary to such an interpretation.

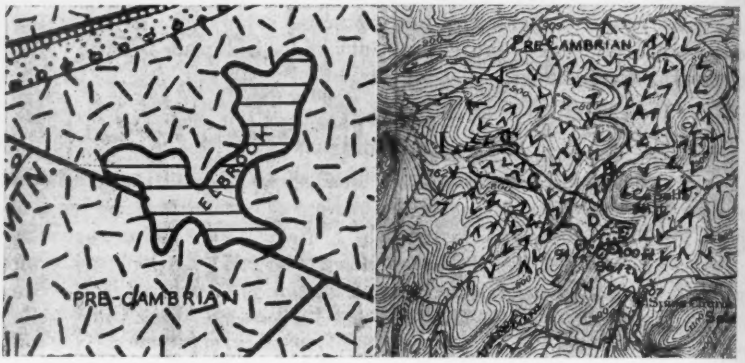
This discussion would be unduly long if each area designated as a "window" were described. For that reason, several typical ones have been chosen for description.

ANTIETAM COVE

The area on the headwaters of Antietam Creek, Alsace Township, north and west of Capella Hill, designated as a "window" (Fig. 8; Pl. 5), is selected because it would be difficult to interpret it otherwise if the Stose-Jonas mapping were accurate. They map it as a very irregular area somewhat more than a mile long, floored with Elbrook limestone and completely surrounded by pre-Cambrian rocks. The general shape and topographic features are shown in Figure 8, in which the Stose-Jonas lines have been transferred to the topographic map.

The "window" is confined to the flat areas north, west, and southwest of Capella Hill (Fig. 8). In the entire flat, which is swampy in places, not a single outcrop has been found.

The wide north portion and the narrow part west of Capella Hill contain abundant blocks of basic gneiss. Some of the blocks near the tiny stream that flows through the flat are 12 to 14 feet in diameter and bear no evidence of transportation (Pl. 1, fig. 2). The surrounding hills of gneiss are in places approximately ¼ mile distant,



A B

FIGURE 8.—*Antietam Cove "window"*

A (left). Photostatic enlargement from Stose and Jonas maps. The irregular central area is mapped as a "window" of Elbrook limestone surrounded on all sides by pre-Cambrian rocks of the "overthrust block."

B (right). "Window" of Stose-Jonas outlined on topographic map. The formation boundary lines of the "window" roughly conform to the limits of the comparatively flat area which is what was probably intended. At A, B, and C the entire area is strewn with hugh gneiss boulders and no trace of limestone. At D a few pieces of jasper were found in stream deposit. At E occur many pieces of Hardyston sandstone. Interpretation is that major part of entire "window" is valley cut in gneiss. A small block of Hardyston is present in southeast portion. Limestone, probably Tomstown, may be present in vicinity of D. The three wells at border of "window" showed gneiss from top to bottom. According to the "overthrust" interpretation of Antietam Cove as a "window" of erosion all three of these wells should have been mainly in limestone (Elbrook?) and have yielded hard water. The water is soft.

Scale: 1 inch = 1 mile approximately.

precluding that these huge blocks are talus. It therefore is more logical that the north portion of the flat area is floored with gneiss and not limestone and therefore is not a window.

In the southern portion of the "window" there are similarly no outcrops, but across the road from the Alsace Township school and slightly to the north several pieces of Hardyston sandstone were found. Also in an excavation along the small brook somewhat farther west a few pieces of jasper were noted. The gneiss boulders in this southern portion are less numerous, and some limestone may be present there. Since the Tomstown lies on top of the Hardyston, the writer has represented this formation as possibly present where the two streams join, with a normal fault separating it from the gneiss on the west side.

The failure to show Hardyston which is undoubtedly present in one portion and the representation of limestone of the Elbrook formation in the flat areas of no exposures, with the Tomstown lacking, gives the deceptive appearance of a window. Three wells (Fig. 8B) drilled in recent years at the southeast corner of the "window" shown on the Stose-Jonas maps supply more specific evidence.

At the farm of Chas. Hinkle, a well 94 feet deep was drilled. A neighbor, Elam

FIGURE 1. VIEW ALONG PINE CREEK
Two miles east-northeast of Lobachsville, showing cliff of pre-Cambrian gneiss. Stose-Jonas maps show Elbrook limestone "window" at this point.

FIGURE 2. MASSES OF PRE-CAMBRIAN GNEISS
North portion of so-called Antietam Cove "window".

LOCALITIES OF "WINDOWS"

FIGURE 1. VIEW OF HEADWATER STREAM OF NORTHWEST BRANCH OF PERKIOMEN CREEK
Between Dale Valley and Landis Store, showing angular masses of pre-Cambrian gneiss. Stose-Jonas maps show Tomstown-Elbrook limestone "window" at this point.

FIGURE 2. MASS OF PRE-CAMBRIAN GNEISS BLOCKS
In stream bed of the area shown on the Stose-Jonas maps as an Elbrook limestone "window", 1 mile west-northwest of Devil Head.

LOCALITIES OF "WINDOWS"

Folk, has a well 96 feet deep, and the well at the new Alsace Township School is slightly over 100 feet deep. These three wells encountered gneiss only, although, according to the "overthrust" hypothesis, Elbrook limestone should be a few feet from the surface inasmuch as the sites are only 10 to 20 feet above the level of the flat ground where the limestone is shown on the Stose-Jonas maps. All the wells yield soft water.

A flat, swampy, somewhat smaller area in basic gneiss, less than $\frac{1}{2}$ mile west of the north portion of the "window" and about 100 feet higher, is similar topographically to Antietam Cove. There is complete agreement that this is floored by basic gneiss and demonstrates the erosional development of flat areas where there is no limestone. The Stose-Jonas maps show pre-Cambrian rocks here. Topographic features such as those of the Antietam Cove, therefore, cannot be interpreted as indicative of limestone and consequently a "window" without other confirmatory evidence.

OLEY VALLEY

The Stose-Jonas maps and sections indicate that the conjectured overthrust sheet passed across the wide attractive Oley Valley (Figs. 1, 12; Pl. 5) somewhat above the existing floor. According to them, erosion has removed a large portion of the block that came to rest on the limestones, exposing them as a "window."

Several different types of evidence indicate the fallacy of such an interpretation. Of foremost importance is the record of the core drill holes on Shenkel Hill.

A second line of evidence is the presence of continuous exposures of Hardyston sandstone along the east side of Oley Valley. Actually, this band of Hardyston is even more continuous than shown on the Stose-Jonas maps. In their structural section (1935a, Fig. 7B, p. 774) across Oley Valley they show the Hardyston on the flank of the mountain but ending at about the level of the valley. The evidence that the Hardyston does not continue under the limestone of the valley in a perfectly normal manner seems to depend on their assertion that the Tomstown is lacking and that Elbrook or Conococheague is in contact with the Hardyston.

E. T. Wherry on an unpublished map shows Tomstown in contact with the Hardyston along the east side of Oley Valley in normal sequence. Wherry states that, in the absence of outcrops, he considered the presence of shale flakes in the soil as evidence of the Tomstown. In this connection, it may be noted that the name "Tomstown Dolomite" may be somewhat misleading in that the formation contains occasional shale lenses. These have been noted in many outcrops and in some of the old limonite iron mines. Stose and Jonas (1935a, p. 767) say that "the quartzite in the hills east of Oley Valley also dips west toward the limestone valley, but there also the limestone is Elbrook and Conococheague and not Tomstown."

Over a wide area, up to $\frac{3}{4}$ mile from the Hardyston, there are no exposures of bedrock, and the mapping of Elbrook and Conococheague in this region is purely arbitrary. The mapping of Elbrook limestone in Manatawny Cove, which is an offshoot from Oley Valley, is likewise without evidence as exposures of limestone are lacking. Even if Stose and Jonas have identified certain limestones in Oley Valley as Elbrook, there is still a band without exposures adjoining the Hardyston sufficiently wide for the outcropping of the Tomstown.

Near Spangsville the Hardyston is exposed in a sand pit at a lower level than some of the "overridden" limestones of the Valley. The writer is inclined to assume that the normal order prevails when exposures are lacking and therefore believes that the Hardyston strata dipping toward the limestone valley pass beneath Tomstown strata in normal manner. For one to assume abnormal relations is to accept the burden of proof.

If Oley Valley is a "window" formed by the removal of a 5-mile width of the overthrust block of pre-Cambrian rocks and thousands of feet of overlying Paleozoic strata, it is amazing that the valley level is almost exactly at the level of the sole of the "overthrust." For 5 miles in a remarkably straight line the "window" is bordered by the Hardyston sandstone dipping toward the limestone but not passing under it, as shown on the Stose-Jonas structural section (1935a, Fig. 7B), a situation not impossible but most unlikely. With a window developed by the erosion of a sheet composed mainly of pre-Cambrian rocks at the base, thrust "northwestward on a flat fault plane," one would certainly expect the trace of the fault to be far more sinuous and irregular than the east side of Oley Valley, and the Hardyston less regular and less persistent.

At the west side of Oley Valley normal faulting has taken place. Stose and Jonas indicate that the limestones of the valley "window" have moved upward relative to the bordering gneiss hills, whereas the writer believes they have moved downward.

The writer and other Pennsylvania geologists believe Oley Valley is a typical syncline with the Hardyston outcropping on the east side and bounded by normal faults on the west which have dropped the Hardyston and some of the overlying strata from sight. Stose and Jonas recognize this type of structure as common throughout the region. They have mapped more than a score of such structures on their "overthrust sheet" (1935a, Pl. 52) and also the overridden stationary block (1935a, Pl. 53). They say that "the overthrust block evidently was much fragmented during overthrusting for it is broken by numerous normal faults, most of which reach its borders but do not affect the valley rocks." Their maps show the same abundance of normal faults in Irish Mountain, which supposedly was not moved. This fragmenting of the stationary block is not explained. Their maps of both blocks show normal faults on the north, northwest, and west of practically all Hardyston areas within the pre-Cambrian rocks. The only difference between the synclines they map on both the "stationary" and the "overthrust" blocks and Oley Valley is size.

Thus, unless specific evidence is presented to show that the Tomstown does not border the Hardyston on the east side of Oley Valley and the Hardyston dipping toward the valley does not continue under the limestone, one cannot accept the "window" interpretation.

SAUCON VALLEY

The general situation in Saucon Valley (Fig. 1) has been discussed. Saucon Valley is like Oley Valley in that both are bordered by pre-Cambrian crystalline rocks and floored by Paleozoic limestones. The same arguments used in the discussion of Oley Valley apply to the Saucon Valley.

DALE VALLEY

Miller and Fraser (1935, p. 2032) called attention to the presence of more Hardyston than Stose and Jonas show on their map of Dale Valley (Pl. 5).

Dale Valley presents structural problems that, in detail, cannot be solved without more exposures. The great areas of Hardyston sandstone on the northeast and southwest sides with a definite fault on the northwest and probably another one extending the full length of the southwest side suggest a syncline trending northwest-southeast but faulted at both ends.

All the known facts fit into the interpretation of a down-folded and faulted block and not a "window."

Stose and Jonas show another limestone "window" a short distance west of and connected with Dale Valley by a narrow band of limestone. A peculiar feature of their maps here is that a small area of Hardyston sandstone of the overridden block is in contact with another similar bit of the same sandstone in the overriding block (1935a, Pls. 52, 53). It seems most unlikely that a series of beds, probably less than 100 feet thick, should be transported 15 to 25 miles and come to rest in contact with beds of the same formation, of the same lithologic characteristics and same trend as those of the stationary block. There is a great deal more Hardyston along the east side of the designated "window" than their maps show. No limestone is exposed, but it may be present in the swampy ground west of the Hardyston. If so, it should be Tomstown, which belongs normally above the Hardyston.

The narrow valley connecting this area with Dale Valley, through which a headwater stream of Northwest Branch of Perkiomen Creek flows, is shown (Stose and Jonas, 1935a, Pls. 52, 53) as a Tomstown-Elbrook limestone "window." Actually the valley is floored and choked with large blocks of basic gneiss (Pl. 2, fig. 1).

ONE MILE EAST OF HILL CHURCH

Stose and Jonas show a small area of Hardyston quartzite and Tomstown limestone in a "window" (Pl. 5) about a mile east of Hill Church and about 1½ miles west of Eschbach on the Fronheiser Farm.

> "West of Eschbach there is a wide belt of mylonitized granite, which surrounds a small window containing Tomstown dolomite and the upper beds of Hardyston quartzite exposed in the old Fronheiser quarry." (Stose and Jonas, 1935a, p. 773)

Investigations confirm the presence of a small area of metamorphosed, crumpled and sheared quartzite, limestone, and gneiss. The limestone was once quarried in a small opening and burned for lime in a near-by kiln. The exposures show the limestone butting against the mylonitized gneiss but not passing under it as implied in the overthrust hypothesis. Gneiss seems to surround the small patch on all sides. A sand pit in the decomposed gneiss along the highway a short distance east of the limestone quarry is 50± feet lower. To have the sole of the "overthrust" below the sand pit and above the limestone would require complex folding or faulting, or both, subsequent to the "overthrusting," for which no evidence has been presented. In addition, the occurrence is on the hillside at an elevation of about 560± feet, as shown on the topographic map, and not near the floor of the near-by small stream

valley. This is roughly 150 feet higher than the hypothetical thrust plane at Eschbach to the east and in Oley Valley to the west and is not in accordance with a "flat thrust plane" as shown in the Stose-Jonas sections and described in the text.

The presence of gneiss both higher and lower on the hillside, coupled with the fact that the crumpled limestone and sheared gneiss are in unconformable contact at the same level, seems to prove that it is a block of Paleozoic strata down-faulted into the pre-Cambrian rocks.

PINE CREEK VALLEY

The Stose and Jonas map (1935a, Pl. 53) shows Pine Creek valley as a "window" of Elbrook and Tomstown limestones and describe it as such (p. 771).

This is incomprehensible, inasmuch as a ledge of gneiss close to the highway is well exposed in the bottom of the valley slightly less than 2 miles east of Lobachsville (Pl. 1, fig. 1) where Elbrook limestone is mapped. Both upstream and downstream from this place the valley floor is strewn with masses of gneiss boulders.

They also state (1935a, p. 772–773) that "abundant chert . . . is found throughout the floor of the Pine Creek-Seisholtzville-Zionsville valley." This does not apply to Pine Creek valley except in the lower portion where the stream cuts across the Hardyston sandstone.

MANATAWNY COVE

On the Stose-Jonas maps (1935a, Pls. 52, 53) of Manatawny Cove, Elbrook limestone of the overridden block is in contact with Hardyston sandstone of the overriding block on the southeast side of the valley. The section (1935a, Fig. 7C, p. 776) presented by Stose and Jonas shows an extraordinary situation. The Hardyston on the south side is explained as a small remnant of a synclinal fold of the "overthrust" block in which the trough of the syncline is the basal conglomerate. The bottom of the syncline is exactly at the sole of the fault bringing the Hardyston in contact with Elbrook limestone of the overridden block. Proof for such a remarkable coincidence is lacking, as is also the reason for assigning any limestones present to the Elbrook.

E. T. Wherry (unpublished map) assumed that the Hardyston sandstone dipped normally beneath the limestones forming the floor of the Cove and that the limestones possibly forming the floor belong to the Tomstown. There are no limestone exposures, only shale flakes in the soil, interpreted as Tomstown. The writer likewise believes that the Hardyston dips beneath the concealed limestone in normal order and that the limestone in contact is the Tomstown. In that case, Manatawny Cove likewise should be dismissed as a "window" until evidence of the Elbrook age of the unexposed limestones is produced.

In fact, Manatawny Cove illustrates very well the type of structure common in the Reading Hills. On the southeast or east side of valleys the sedimentary formations dip away from the gneiss on the north, northwest, or west, and the formations form bands of increasing youth from the gneiss hills outward. The other side of the valley is commonly bounded by a normal fault that has brought the Cambrian or Ordovician formations in contact with the gneiss. In other words, Manatawny Cove

is interpreted as a syncline that has been broken by a normal fault on the northwest side.

VERA CRUZ "WINDOW"

The distinctive features of the so-called "window" extending westward from Vera Cruz is that the maps (Stose and Jonas, 1935a, Pls. 52, 53) represent the Hardyston quartzite in discontinuous patches along the sides of the valley, some of which are part of the "overthrust" sheet and some part of the over-ridden block. At one place Hardyston patches of the two blocks are in contact. They are in alignment which suggests like structural history. The writer vouches for the statement that the lithologic characteristics are so similar that they could scarcely have been deposited in localities 15 to 25 miles apart, especially since the Hardyston strata are so variable. Also there seems to be little question but that considerably more Hardyston is present than is shown.

THREE-FOURTHS MILE WEST OF HILL CHURCH

Three-fourths of a mile west of Hill Church and about 2 miles east of Manatawny in Pike Township, Stose and Jonas map an irregular window of Elbrook limestone surrounded by pre-Cambrian rocks except for a small slice of Hardyston sandstone in the overriding block in contact with the limestone on the southeast side of the "window" (Figs. 9, 12; Pl. 5).

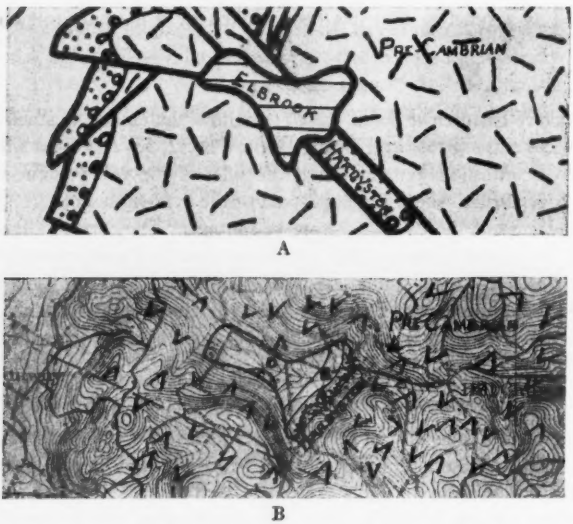
Abundant Hardyston sandstone is present all along the eastern side of the area in contact with the gneiss and not alone in the restricted portion shown. The farmers have built fences of the white sandstone about their farms. Westward from the sandstone-strewn portion there are other boundary fences of irregular large and small pieces of jasper gathered from the fields. The distribution indicates the superposition of the jasper immediately above the sandstone ledges, and thus the sandstone and jasper float are in normal distribution. No jasper was seen in place.

Westward from the jasper-strewn fields there are no outcrops, but the flat, somewhat swampy ground may indicate that limestone is present. Along the south side of the so-called "window" there is also a small area of Hardyston sandstone float.

The data at hand indicate that this is a typical Reading Hills down-dropped block of Paleozoic sediments and that such limestone as may be present should be Tomstown. The representation of only part of the Hardyston and the reference of the limestone to the Elbrook, with the Tomstown lacking, favor the overthrust hypothesis, but the writer's investigations lead him to conclude that it is more logical to believe that the normal sequence prevails here—*viz.*, gneiss, Hardyston, Tomstown (Fig. 9).

DEVIL HEAD

One mile northwest of Devil Head and $1\frac{1}{4}$ miles northeast of Landis Store, Stose and Jonas map a small irregular "window" of Elbrook limestone surrounded by pre-Cambrian rocks (Fig. 10). The flat area along the small stream reveals no rock in place but is covered with blocks of gneiss (Pl. 2, fig. 2) presenting the characteristic features of a valley cut in the gneiss. There are numerous localities where local flat



A

B

FIGURE 9.—*"Window" three-fourths of a mile west of Hill Church*

A (upper). The Stose-Jonas maps show a "window" of Elbrook limestone bordered by pre-Cambrian rocks of the "overthrust block" on all sides except on the southeast where a peculiar wedge of Hardyston is shown in contact with the Elbrook limestone. There are no exposures of limestone. Their map is in error in that much more Hardyston should be mapped along the eastern border. No reason has been advanced for representation of Elbrook.

B (lower). The writer's interpretation. Exact boundary lines cannot be drawn because of absence of rock in place. A band represented by *A* contains an abundance of Hardyston white sandstone float (stippled area). A small patch at *C* shows the same float material. The band *B* shows an abundance of jasper and indicates the outcrop of a chert band adjoining the sandstone strata. The float extends considerably farther west than the delineated bands. The greater portion of the valley shows little Hardyston float. It is probably underlain by limestone, and the most likely formation is Tomstown in normal succession above the Hardyston.

Scale: 1 inch = 1 mile approximately.

A B

FIGURE 10.—*"Window" a mile west of Devil Head*

A (left). Stose and Jonas show this small valley with a relatively flat bottom as a "window" of Elbrook limestone surrounded by pre-Cambrian rocks of the "overthrust" block.

B (right). The topographic map shows the character of the "window." No evidence of limestone. The whole surface is strewn with large and small masses of gneiss. (*See* Pl. 2, fig. 2.)

Scale: 1 inch = 1 mile approximately.

areas of erosion develop in the pre-Cambrian gneisses. Without any evidence of limestone this area should not be termed a "window."

OTHER "WINDOWS"

The Limeport (Fig. 1) "window" of Plate 53 (Stose and Jonas, 1935a) reveals only Tomstown dolomite, Elbrook limestone, and a small patch of Martinsburg shale surrounded by pre-Cambrian gneiss of the "overthrust" block. The absence of

Hardyston here favors the "overthrust" hypothesis. However, the writer claims that the abundant jasper and occasional pieces of sandstone in the soil and in the dump of an old iron mine indicate the presence of Hardyston.

The long narrow "window" extending from Hereford to Boyertown, about 10 miles, between the pre-Cambrian gneiss on the northwest and the Triassic on the southeast (Stose and Jonas, 1935a, Pls. 52, 53) is mapped as floored with Tomstown dolomite with small patches of Hardyston quartzite, of which five are assigned to the "overthrust" sheet and seven to the "overridden" block.

In this area there are few outcrops of the Hardyston but considerable float. All the material observed by the writer consisted of white to gray quartzite with some pebbly beds. The similarity is so striking that it seems most improbable that part originated 15 miles away in view of the lithological variability of the Hardyston. The writer believes that the band of Hardyston is practically continuous bordering the gneiss and possibly beneath the Tomstown in normal sequence. Here and there the unit is interrupted by local faults of minor displacement. In some places the Hardyston rises high in the hillsides, while elsewhere it has been removed from the higher slopes and appears only at the base of the gneiss hills.

The long narrow "window" (Pl. 5) south and southwest of Topton Mountain, through which a headwater stream of Sacony Creek flows, is extremely problematical. Plate 53 (Stose and Jonas, 1935a) shows Tomstown dolomite in the floor with a few small patches of Hardyston. Along the highway, which closely follows the stream for some distance, gneiss in place can be seen close to the stream, and great angular blocks of gneiss choke the stream. No gneiss outcrop has been observed in the stream channel, but the general appearance indicates the absence of any limestone in this so-called "window."

A minor argument opposed to the view that some of the flat places in the gneiss hills are limestone "windows" is the absence of sink-holes.

E. T. Wherry (personal communication) has made extensive studies of the distribution of native plants in relation to soil conditions. He finds that certain plants, especially members of the heath family, such as blueberries, are intolerant of limestone soils, whereas other groups of plants may indicate the presence of lime in a soil. He says there is no ecological evidence of limestone in those flat areas that have been termed "windows" of limestone by Stose and Jonas.

SUMMARY OF "WINDOW" EVIDENCE

In general, the evidence presented by Stose and Jonas in support of their belief in the interpretation of certain fairly flat regions along stream valleys as "windows" of erosion in the "overthrust" sheet is shown on their maps where either the Hardyston or the Tomstown strata is lacking and the Elbrook is in contact with the pre-Cambrian crystalline rocks. In each of the "windows" discussed, the writer has attempted to show that there is no evidence of this discordance. In several instances he is convinced that portions of the Hardyston have been omitted and that, in every instance investigated, because of absence of exposures there is no evidence that the limestone that may be present is Elbrook rather than Tomstown.

For certain "windows" the writer has presented tangible evidence that limestone is definitely not present, and in other cases it is most improbable. The hypothesis also results in several inconsistencies.

In closing the discussion of "windows" one may remark that with "windows" so numerous it seems strange that, in none except the one described east of Hill Church, has anyone reported the contact of the pre-Cambrian rocks and the Paleozoic limestones. It would seem most probable that at several places the fault plane would be above the valley floor so that it might be seen even with due allowance for the accumulation of talus. Also, it is peculiar that erosion has proceeded just far enough to bring the floor of the "windows" to the level of the sole of the fault and that this is almost, if not quite, the same elevation as the limestone valleys that are not interpreted as windows.

PHASES OF THE HARDYSTON FORMATION

One of the controversial problems involves the composition of the Hardyston formation, which is considered Lower Cambrian and comprises the earliest Paleozoic sediments of the region.

Stose and Jonas (1935a, p. 760) offer the following description:

> "... Its basal beds are a pebbly arkosic quartzite or conglomerate, ferruginous and purple-red in color, and contain pebbles of feldspar and jasper. In many places the basal beds of the Hardyston are composed of pink feldspar, quartz, and dull-green amorphous-looking mineral that has been called pinite, but in thin section is seen to be made up of a felty mass of fine green muscovite.... The main part of the formation is thick-bedded vitreous blue or white quartzite which in the upper part is thinner bedded, finely feldspathic, and contains *Scolithus linearis*. The recognition and separation of these distinctly different beds of the Hardyston quartzite are essential to the working out of the structure of the area."

They further state (1935b, p. 2039): "We claim that the stratigraphic section of the Hardyston quartzite given in our paper is constant throughout the area, as can be demonstrated in the field."

The quoted description is correct for certain sections but not for others in the Reading Hills. Actually the Hardyston presents more varied lithologic features than any other sedimentary formation of the region. This variability occurs not only in the vertical range of the beds but also along the strike and in very short distances. Certain features are peculiar to only one or a few local outcrops. It contains different types of conglomerates, sandstones, quartzites, jasper (or jasperoid), chert, shales, and locally the metamorphosed material called pinite. The arenaceous phase has generally been termed quartzite. This is a correct designation in many places where it is a structureless, almost glassy, quartzite. In more localities metamorphism has been of minor effect, and it is more properly called sandstone. The thickness also ranges from a few to several hundred feet.

Specimens of *Scolithus linearis* are abundant in certain localities, rare in others, and apparently absent in many others. In addition, another species of *Scolithus* (to be described) is present in the Allentown district.

These variations in the lithologic and paleontologic characteristics of the Hardyston can be demonstrated in the field. Correlation of beds within the formation on the basis of lithology is possible only in local areas, and the method must be used with extreme caution in structural interpretations. To introduce faults wherever one or another lithologic type is lacking can lead only to hopeless confusion.

One illustration of the variability of the Hardyston is cited although many might

be given. In Mt. Penn, Deer Path Mountain, Irish Mountain, and other places in the Reading quadrangle there is a type of sandstone that readily disintegrates. Great sand quarries have been opened in it. Eastward this type of material is absent, and decomposed gneiss has been worked instead for sand for local use.

JASPER

GENERAL STATEMENT

One topic about which disagreement exists is the jasper. It might be well to call the material jasperoid, but the common usage is adopted here.

This material is well developed in some places and lacking in other places where the Hardyston sandstone is present. The jasper occurs in close association with the sandstone and occupies a definite stratigraphic horizon above the sandstone, as can be shown in the field both by rocks in place and by distribution of float. It is somewhat more variable in physical characteristics than some of the other phases of the Hardyston. It can be studied to good advantage in the localities where the Indians quarried it for implements.

The writer has included the jasper in the Hardyston because evidence shows that some of it has replaced sandstone, but he readily admits that there is some evidence, such as the near-by presence of shale, for considering it as basal Tomstown. When certain unusual deposits lie between two conformable formations it is of little structural consequence as to whether the beds in question be included in the top of the lower formation or at the base of the overlying formation.

The origin of the jasper has been discussed in several articles (Miller, 1925; Myers, 1934; Fraser, 1937; 1938). Some unsolved problems remain, and further research must be done before positive conclusions can be reached.

It is well to call attention to the difference between the cryptocrystalline siliceous materials found in the Hardyston and those of the Paleozoic limestones of the region. With few exceptions the product associated with the Hardyston sandstone is taffy-yellow jasper, much brecciated and prominently cavernous. The interior of the angular cavities in many places is coated with white or purple chalcedony or clear drusy quartz. There are prominent brown and red varieties also. Jasper occurs in great masses and makes cliffs in a few places. On the lower slopes of the hills and extending outward in the limestone areas, abundant angular blocks of the material strew the surface. In most places where it is present *in situ* one can find numerous old limonite mines. The ore is of the "mountain" type. Specimens show plainly the transition from jasper to ore. Blocks encountered in mining were thrown on the dumps. Unusually large masses were left standing in some mines. Stratification or bedding planes are not apparent.

On the other hand, the cryptocrystalline silica segregations in the limestones are typically black chert (flint) in irregular shapes although generally rounded. They show little brecciation. They have originated by replacement of the limestone as evidenced by the fact that fossils have been found composed entirely of chert. Rarely can bedding planes be noted. Nodules of the black chert seldom exceed 1 foot in diameter except where developed along bedding planes. Layers a few inches thick may be 10 feet long. Residual black flint nodules are common in the limestone soils of the region.

A less common variety in the limestones is the milky white to opalescent gray chert. A few masses exceeding 5 feet in diameter are known. The writer's observations indicate that this gray chert is normally developed along bedding planes and may possibly have been deposited as a siliceous ooze when the limestones formed.

Almost everywhere the jasper of the Hardyston and the chert of the limestones can be positively distinguished, but occasionally the writer has picked up specimens of cryptocrystalline silica in the limestone areas that are somewhat similar to the Hardyston variety, and vice versa.

The important matter in this discussion is the distribution and stratigraphic position of the jasper of the Reading Hills. Stose and Jonas (1935a) say

> "This chert is . . . derived from the replacement of limestone by silica along the thrust fault" (p. 772). "Similar cherts are abundant on the mountain border wherever the overthrust is in contact with limestone" (p. 773).

The writer is convinced that the jasper has been formed in place, possibly as an original deposit but more probably and mainly by the replacement of Hardyston sandstone and shales (perhaps in part calcareous). Opposed to this view of the writer is that of Stose and Jonas (1935a) who say:

> "The chert and jasper was produced by silicification of the limestone along the thrust fault and is evidence of the presence of limestone in valleys within the mountains where limestone does not crop out." (p. 773)

To illustrate the writer's contention, certain specific and typical localities are described.

OLEY VALLEY

If the jasper were formed along the sole of the "overthrust," one of the most likely places in the area to find it would be in the broad Oley Valley, which the Stose-Jonas maps (1935a) show as a "window" of Cambro-Ordovician limestones and Martinsburg shale. The section presented (1935a, p. 774) shows that the overthrust block passed across the valley only a short distance above the present surface. The conditions would seem to be most favorable for the development of jasper if its place of formation is along the sole of an overthrust. Because of its resistance to weathering, one should expect to find abundant fragments of jasper in the existing soils intermingled with the residual black flints of the limestones. The writer's observations indicate that all jasper float is confined to the proximity of the Hardyston sandstone outcrops on the eastern side of the valley where the Hardyston directly overlies the pre-Cambrian gneiss.

Stose and Jonas (1935a) recognize this distribution in their statement that "Similar cherts are . . . especially abundant where quartzite on the sole of the thrust is in contact with limestone (Fig. 2)." (p. 773) The implication is that the siliceous waters were more effective in producing silicifications where small masses of Hardyston sandstone (quartzite) constituted a part of the "overthrust." This is questioned inasmuch as jasper is prominently developed in places where the sandstone is less than 20 feet thick and absent in other places where the sandstone is a few hundred feet thick. It also seems probable that waters circulating through the gneisses would become as siliceous as those passing through the sandstones.

FIGURE 1.
NORTHWEST SLOPE OF SOUTH MOUNTAIN
½ mile east-northeast of Emmaus. Hardyston sandstone strata dip 50°-52° NW. beneath an outcrop of jasper. Man in left background stands beside mass of jasper in place.

FIGURE 2. CLOSE VIEW OF PORTION OF JASPER CLIFF SHOWN IN FIGURE 1.
Rough, jagged surface; no bedding planes observable.

FIGURE 1. CLIFF OF MASSIVE JASPER
Over 50 feet in height, northwest slope of South Mountain, half a mile east of Wilbur

FIGURE 2. CLOSE VIEW OF MASS OF JASPER SHOWN IN FIGURE 1
Typical appearance, rough surface, no stratification.

The Hardyston of the "overthrust" is shown on the Stose-Jonas map (1935a, Pl. 52) in contact with Elbrook and Conococheague limestones continuously along the east side of Oley Valley from Earlville to Pikesville—about 5½ miles—and on the south side of Manatawny Cove, about 2 miles. According to the quoted statement, jasper should be present everywhere in this locality. Actually it is conspicuous by its absence. Near Manatawny there are some large masses of jasper float, but elsewhere in this region it appears to be almost, if not entirely, missing.

MT. PENN—DEER PATH MOUNTAIN

According to the Stose-Jonas' statement, there should be abundant jasper along the western slope of Mt. Penn and Deer Path Mountain where their map (1935a, Pl. 52) shows a continuous band of Hardyston of the "overthrust" in contact with "over-ridden" Paleozoic limestone for about 4 miles. In addition there are several other similar occurrences in the vicinity of Reading. The writer has failed to find any jasper here, and inquiry from local residents has likewise been unsuccessful.

These and the Oley Valley occurrences indicate the sporadic distribution of the jasper and suggest lack of association with the sole of the "overthrust."

SOUTH MOUNTAIN, EAST OF EMMAUS

In one of the old limonite mines on the northwest slope of South Mountain half a mile east-northeast of Emmaus, Hardyston sandstone beds dip steeply northwest down the slope beneath a fine exposure of the jasper (Pl. 3). The sandstone and jasper are in apparent conformity, although, as stated above, stratification lines are not definitely determined in the brecciated jasper. The jasper here is about 150 feet above the Cambrian limestone valley level. At this locality the Stose and Jonas maps (1935a, Pls. 52, 53) show no Hardyston, but instead the pre-Cambrian rocks of the "overthrust block" are shown in contact with overridden Elbrook limestone. The idea of "a great overthrust sheet which has ridden northwestward on a flat fault plane in the crystalline core of the mountains over lower Paleozoic rocks" (p. 763) with the jasper formed along the "overthrust" plane does not fit the facts here. This occurrence is the best one known in the region under discussion to show the relationship between the Hardyston sandstone and the jasper.

SOUTH MOUNTAIN, EAST OF WILBUR

The finest exposure of jasper known to the writer is high on the slope of South Mountain east of Wilbur, about 2 miles northeast of Emmaus, close to the eastern margin of the Stose-Jonas maps (1935a, Pls. 52, 53). At this place impressive cliffs of jasper extend up the hill over 100 feet above the limestone of the valley (Pl. 4). Farther up the hill, strata of the sandstone phase of the Hardyston evidently rest on the pre-Cambrian gneiss as determined by pieces of sandstone on the surface. Gneiss crops out on the crest of the mountain. The position of jasper cliff high on the mountain slope does not conform to the descriptions and sections of the proposed "overthrust."

WASSERGASS

At Wassergass (Fig. 1), Northampton Co., 3 miles east of Hellertown, in an old limonite mine the Hardyston sandstone, part of which is decidedly pebbly, is exposed

on the south side of the pit dipping steeply to the north. The waste material contains much jasper, some of which definitely shows the transition stages into limonite ore.

This locality is near the top of the hill with gneiss close by on both the north and south. There seems to be no limestone in this immediate vicinity. The locality is about 200 feet higher than the limestones of near-by Saucon Valley. Presumably Stose and Jonas place the sole of the overthrust not far above the floor of the Saucon Valley. If so, the jasper here can scarcely be attributed to silicification along the base of the hypothetical overthrust.

MINE HILL—RATTLESNAKE HILL

In the col between Rattlesnake Hill (Fig. 1) and Mine Hill, southwest of Durham Furnace, Bucks County, Easton quadrangle, an area of Hardyston contains large quantities of jasper and minor amounts of sandstone. Pebbly sandstone is present, although most of the sandstone is fine-grained. The jasper is mainly of a taffy-yellow color, part of it decidedly drusy. The cavities are lined with quartz crystals and chalcedony. Some of the chalcedony is purplish. In a small grove surrounded by wheat and grass fields, there are nine pits where the Indians dug the jasper for making arrowheads. Thousands of jasper flakes can be found in the field just north of the pits.

Apparently the area is surrounded by gneiss, two separated outcrops of gneiss appearing to the south and southeast and abundant gneiss outcrops on Rattlesnake Hill to the northeast and on Mine Hill to the southwest. Occasional pieces of black flint associated with jasper are interpreted as remnants of some overlying Tomstown limestone which now has been entirely eroded.

The sandstone and jasper between the high hills of gneiss and apparently overlying gneiss indicate a thin remnant of Hardyston which has been folded and possibly faulted downward and has up to the present time escaped entire removal.

This locality is described by H. C. Mercer (1894) who furnishes additional important data including this statement: "A shaft of the Durham Iron Company encountered a solid vein of red jasper under the Indian jasper quarries, at Rattlesnake Hill, at a depth of about 100 feet."

Jasper, approximately 300 feet above the limestone of the adjoining limestone valley floors and continuing underground to the depth of 100 feet, can scarcely be fitted into the Stose-Jonas "overthrust" hypothesis.

VERA CRUZ

On the ridge about $\frac{1}{4}$ mile northwest of Vera Cruz (Fig. 1), Lehigh County, are the most famous Indian jasper mines of Pennsylvania. Mercer (1894) mentions 60 mines or pits at this place. The surface is strewn with cavernous pieces of jasper that could not be used and thousands of jasper flakes. The pits are on the top of the ridge about 100 feet higher than the floor of the valley in Leiberts Gap, about $\frac{1}{4}$ mile to the northwest where gneiss in place is exposed. The sole of the hypothetical overthrust must lie still deeper. The evidence seems to eliminate this extensive jasper development from any connection with such a fault.

The ridge where the jasper pits are located rises to the west. In that direction,

the jasper float gives way to white Hardyston sandstone and then to gneiss, thus again showing the same stratigraphic order of pre-Cambrian crystalline rocks, Cambrian sandstone, and jasper.

As in the other cases cited the Vera Cruz jasper occurrence is definitely not in accord with the Stose-Jonas structural interpretation.

MACUNGIE

About a mile southeast of Macungie Mercer (1934) counted 108 jasper pits. He says that James Garr found evidence of workings 40 feet deep. The jasper pits are on the north slope of South Mountain and are more than 100 feet above the limestone valley floor. Presumably, they are approximately that much above the sole of the suggested "overthrust" although no gneiss is exposed nearby at a lower level. Up the hill from the pits Hardyston sandstone is exposed, and still higher is the pre-Cambrian gneiss.

The Vera Cruz and Macungie occurrences are closely similar and suggest similar structural interpretations.

BOWERS

Slightly less than a mile south of Bowers, almost exactly on the Manatawny-Rockland township line, Berks County, are other Indian jasper pits. The locality is known as Flint Hill (also "Feirshtay Barrick" or "Sacony Barrick"). A small patch of woodland marks the site of the jasper pits of the Indians. Later some of the jasper was quarried for the highways. Pieces of rejected cavernous jasper and thousands of jasper flakes strew the surface. Some of the cavities in the jasper are coated with blue and white chalcedony.

This occurrence is similar to the previous localities in that it is 100± feet above the floor of the adjoining limestone valley. The pits are on the top of a secondary ridge or bench on the north slope of South Mountain. No outcrop of the Hardyston sandstone was seen. However, south of the pits many pieces of sandstone were observed in the fields, and still farther south and at a higher level the pre-Cambrian gnesis appears. The topographic map at this place is poor so that difference of elevation is approximate.

The jasper locality seems to be surrounded by gneiss. The gneiss crops out in the road cut about $\frac{1}{8}$ mile to the west and forms an east-west ridge at a lower level to the north. Shale, such as occurs in the lower Tomstown, has been reported as formerly outcropping near the jasper. The sandstone and jasper appear to form a shallow syncline or down-faulted block in the pre-Cambrian gneiss. The occurrence seems to be inconsistent with the "overthrust" hypothesis.

The Stose-Jonas maps (1935a, Fig. 2; Pls. 52, 53) of the locality are somewhat confusing. They seem to indicate a patch of Hardyston quartzite, part of which belongs to the "overthrust" block and part to the "overridden" block. They show no pre-Cambrian to the north.

SUMMARY OF JASPER LOCALITIES

The nine specific cases cited do not exhaust the available evidence of the stratigraphic position of the jasper in the region; they illustrate the general situation. All

of them show the jasper stratigraphically above the Hardyston sandstone and in apparent conformity. In addition, the jasper occurs generally not at the base of the mountains, where the sole of the "overthrust" is supposed to be, but far up on the slopes and even on or near the tops of some ridges. None of these instances described is in harmony with the "overthrust" hypothesis. Finally, the absence of jasper in wide areas where the pre-Cambrian rocks of the "overthrust" are shown (Stose and Jonas, 1935a, Pls. 52, 53) in contact with Paleozoic limestones of the hypothetically overridden rocks is in direct disagreement with the authors' statement that jasper is developed wherever such conditions exist. Residual jasper should be found abundantly and widespread in the soil of such limestone areas as Oley Valley if they are "windows" and if the sole of the fault passes across them slightly above the existing surface, but this is not the case.

GRAVIMETRIC EVIDENCE

Stose and Jonas (1940) showed contours drawn on the basis of gravity determinations by the U. S. Coast and Geodetic Survey in the vicinity of Bethlehem. This was presented orally as evidence that the crystalline rocks of South Mountain rest upon Paleozoic limestones and thus furnish evidence in support of the "overthrust" hypothesis. Opportunity was not given for a study of the map which has not been published; hence no detailed criticism can be offered. Gravity measurements in the Bethlehem area are pertinent, and the following discussion is therefore presented.

In 1935 gravity measurements were made at 29 stations in the Bethlehem region by the U. S. Coast and Geodetic Survey. The writer and Maurice Ewing studied the results and found no apparent relationship between the surface geology and the gravity measurements. As a further test additional stations were selected, and in September and October 1937 gravity measurements were made in several other places. These results also were studied, but they threw no additional light on the structural problems. Consequently, Ewing and the writer concluded that the data were still inadequate. The definite conclusion was reached that the stations must be much more closely spaced to be of value in determining structure.

In the summer of 1941, J. B. Hersey used a Humble (Truman) gravimeter and occupied some of the former stations and many new ones.[2]

Gravimetric evidence is of value in this discussion only if the obtained readings enable one to determine whether certain rocks at depth are gneiss or dolomitic limestones. The pre-Cambrian crystalline rocks of the region are both acid and basic. The most abundant variety is an acid granite gneiss mainly included in the unit designated as the Byram gneiss. Another fairly common variety is a basic dark-colored gneiss known as the Pochuck gneiss. Other types are sparingly represented.

In the region where the gravimetric readings of the Coast and Geodetic Survey were taken the Byram is the predominant rock of the hills, and dolomitic limestones floor the valleys. It is therefore necessary to detemine whether the densities of these two kinds of work are sufficiently different to be of value in interpreting structure. In this case the specific problem is whether the gravimetric readings will

[2] Hersey's full report is in process of publication by the Geological Society.

reveal the presence of dolomitic limestones beneath the hills of gneiss, the latter having been overthrust on the former, according to the "overthrust hypothesis."

Woollard (1939) determined the specific gravity of a number of gneisses and other crystalline rocks from the Piedmont of Virginia and reached the following conclusion. "Although it is impossible to evaluate exactly the weighted mean density of the basement rocks, it would appear . . . that 2.67 is a fair approximation." (p. 319)

Nettleton (1941) reaches the same conclusion as shown by the following quotation:

"This indicates that the density of the rocks within the range of the elevations of each topographic feature is rather close to 2.67 and, since the different density profiles involve different parts of the geologic section, it constitutes rather strong additional evidence that the densities of the sediments involved in the folds and faults are quite uniform and with a value of about 2.67. Thus the fact that gravity expressions of local structure in the Paleozoic sediments are weak or absent is adequately explained." (p. 275)

"From this rather meagre evidence it seems probable that the density of the basement rocks is not much greater than that of the overlying sediments and therefore gravity will not indicate whether or not the basement rocks are involved in the folds." (p. 275)

Hersey has furnished the following data (personal communication):

"From density determinations in the region the following density contrasts are to be expected:

	Density	Density Contrast
Pre-Cambrian—		
Paleozoic:		
Pochuck	3.0	0.35–0.39
Byram	2.61–2.65	
Pochuck	3.0	0.2 –0.35
Dolomitic limestone	2.65–2.8	
Byram	2.61–2.65	0.0 –0.19
Dolomitic limestone	2.65–2.8	

Examples of anomalies due to each of these contrasts are found in the region, as well as certain others due to density contrasts in the Ordovician sedimentary section in the northern part of the region."

In a letter Hersey adds the following statements:

"Pre-Cambrian areas cannot be recognized by higher gravity values. . . . At most the density contrast between the Byram and Cambrian and Ordovician dolomitic limestones is about 0.19 gm./cc. This sort of contrast apparently obtains at Camel's Hump (an outlier of gneiss about three miles north of Bethlehem) where the Byram is the lighter material. On the basis of what density measurements I have, the Byram would always be the less dense, though it is entirely probable that in many cases there would be little or no contrast between them."

The Pochuck was intruded by the Byram. The field relationships of the gneisses are extremely complicated. If, in any specific locality, gravimetric data point toward lighter material beneath exposed basic gneiss, there is no way of determining whether the underlying rock is dolomitic limestone or acid gneiss.

Accepting Hersey's statements that gravimetric readings in the Bethlehem region reveal the presence of the basic gneiss (Pochuck) but do not permit a differentiation between the more acid gneiss (Byram) and the associated dolomitic limestones, it seems evident that gravimetric determinations thus far obtained in the Reading Hills near Bethlehem do not afford evidence either in support of, or in opposition to, the "overthrust" hypothesis.

The gravimetric data in the vicinity of Minesite, where there is a small exposure

of pre-Cambrian gneiss along Little Lehigh Creek close to Western Salisbury Church, are also of value. Stose and Jonas (1935a) refer to this locality as follows:

"These klippen are close to the front of the overthrust sheet, but the isolated hill near Minesite, which is also an erosion remnant of the overthrust mass, is 3 miles north of the mountain front and marks the minimum northward extent of the overthrust movement." (p. 770)

Hersey describes the locality as follows:

"In the Salisbury Church area the pre-Cambrian outcrop is exactly at the center of a very high gravity anomally that falls off rather rapidly in all directions from the outcrop. Therefore on the basis of present evidence it seems most likely that this anomaly is due to a large mass of material, say, having roughly the size of a sphere a mile in diameter, extending very nearly to the surface, and having a density close to that of Pochuck (3.0 gm./cc.). Since no material other than Pochuck having such density and dimensions would normally be expected in this region, and since the high point of the anomaly correlates perfectly with the position of the pre-Cambrian outcrop I conclude tentatively that the anomally is due to Pochuck surrounded by either Byram or limestone, or both.

"The geologic field evidence indicates that the structure here is an up-faulted block of pre-Cambrian material surrounded by limestone. This interpretation is corroborated by the gravity data."

On the basis of field evidence, presented by Miller and Fraser (1935, p. 2037–2038), the hill in question is interpreted in the same manner as an up-faulted area of pre-Cambrian gneiss and is not believed to be a klippe.

OTHER CONSIDERATIONS OF THE "OVERTHRUST" HYPOTHESIS

SERIES OF EVENTS

The proponents of the "overthrust" hypothesis have not presented a connected story of the events preceding and following the overthrusting. The final paragraph of their original article (1935a) does contain the following sentence: "The writers are inclined to the view that the folding and the overthrusting which produced the Reading-Boyertown overthrust sheet took place during Appalachian orogeny" (p. 779).

It seems pertinent to offer a probable summary of events and a statement of the probable conditions existing before, during, and succeeding the "overthrusting."

In the region under discussion presumably the entire thickness of Cambrian and Ordovician sediments as well as an additional thickness of pre-Cambrian rocks were involved in the folding of this period. Further some geologists think that great thicknesses of Silurian, Devonian, and possibly Mississippian and Pennsylvanian sediments also were present in the area before the Appalachian Revolution. The authors (Stose and Jonas, 1935a, Figs. 7B, 8C) show the entire thickness of Cambro-Ordovician limestones and overlying Martinsburg shales as originally present as part of the "overthrust" block and a thickness of pre-Cambrian rocks, long since eroded, approximately as great as that of the limestones. Since these aggregate approximately 10,000 feet we may therefore assume that the thrust plane was buried to that depth and possibly much deeper when overthrusting took place. The roots of this transported overthrust sheet "are buried beneath the Triassic sediments" (Stose and Jonas, 1935a, p. 775) which means that, at a minimum, the block moved about 15 miles.

As the "overthrust" mass moved northwestward it must have sheared off several thousand feet of strata of the overridden block and pushed the mass ahead of it.

One may well assume that some rocks of the region would be pushed almost if not quite to the present site of Blue (Kittatinny) Mountain.

Presumably, erosion was going on while the block was being moved and has continued ever since. The amount of the "overthrust" block that has been removed from the area would seem to be more than 97 per cent, inasmuch as the remnants of the "overthrust" sheet that constitute the existing Reading Hills represent a thickness of only a few hundred feet, according to the sections presented, and are composed mainly of the pre-Cambrian crystalline rocks with thin patches of Hardyston quartzite and a few slivers of Tomstown limestone.

The most striking portion of this history is that erosion has reached a stage just sufficient to cut through the overriding block in those valleys designated as "windows" and to within a few hundred feet of the base in the hill region. The sole of the overthrust supposedly lies just at the base of the gneiss hills which border the "windows."

Strangely enough, the level of the limestone "windows" corresponds almost if not quite exactly to the erosion level in the limestone valleys of the Great Valley that were never covered by a great sheet of transported material, the lower portion of which was composed of rocks far more resistant than the Paleozoic limestones and shales.

If the thrust plane was subsequently folded and faulted, as has been implied in discussion but not shown on the published sections, one might expect to find the sole of the "overthrust" in some places at levels considerably higher than the bases of the existing hills. No instance of this has been noted.

With this setting, which seems to be in agreement with the proposed hypothesis, several specific problems are presented.

IRISH MOUNTAIN

The most difficult problem, according to the "overthrust" hypothesis, involves Irish Mountain, which forms a salient in the Reading Hills and is explained by Stose and Jonas (1935a) as follows:

> "Along the north border of the mountains are ridges of quartzite and pre-Cambrian rocks which are not part of the overthrust but are anticlines that have risen out of the limestone in front of the advancing overthrust block. The Irish Mountain mass, which forms the front line of hills north of Reading from Temple northeast to Dryville, is an anticlinal uplift of pre-Cambrian rocks and Hardyston quartzite in which the quartzite dips normally northwest and west under Cambrian (Tomstown) limestone, which is overlain, in turn, by the younger limestones of the valley and the Martinsburg shale. . . ." (p. 763)
>
> "East of Temple, the north border of the thrust block lies south of the Irish Mountain anticline, which apparently rose in front of the advancing overthrust and blocked its forward movement." (p. 768)

The writer has studied the areas bounding Irish Mountain on the south and on the east and has failed to discover any evidence of differences between what Stose and Jonas represent as a stationary block and the transported material of the overthrust on both sides (Fig. 11; Pl. 5). The topographic front of Irish Mountain changes from a north-south to a northeast direction without any break. The topographic features of the west side of the mountain are in perfect alignment with the adjoining portion of the "overthrust" block between Frush Valley and Temple. Likewise,

there is no change in the front where the "overthrust" is in contact with the stationary block in the vicinity of Dryville. The Stose-Jonas maps show discordant geologic features in the vicinity of Temple which the writer has failed to find after careful search. They show pre-Cambrian rocks of the "overthrust" in the mountain front north of Frush Valley in contact with Tomstown limestone of the overridden block and Hardyston of the "overthrust" in contact with Hardyston of the overridden block. Several other geologists accompanying the writer to this locality have likewise failed to find any discordance. Therefore, the Stose-Jonas mapping at this place is challenged.

As additional evidence that there is no discordance here, the west flank of the mountain front of both the stationary Irish Mountain and the "overthrust" sheet is composed of Hardyston sandstone of a peculiar type. The Stose-Jonas maps (1935a, Pls. 52, 53) are in error in that the Hardyston of the "overthrust" at this point is not discontinuous as shown. With the exception of occasional layers, the Hardyston here is clean white sandstone easily crushed for commercial sand. Four large sand quarries have been opened in the mountain front north of Frush Valley in the "transported" block and two in the "stationary" Irish Mountain in the same kind of sandstone in line with the western flank of the "stationary" Irish Mountain. The six pits are in close alignment although apparently the same beds were opened at somewhat different levels.

To anyone familiar with the variability of the sandstone of the Hardyston formation it is almost inconceivable that a distinctive type of sandstone should have been transported 15 or more miles and brought to rest adjoining and in line with the same type, especially in view of the fact that the Hardyston represents so small a portion of the "overthrust" block.

A still more remarkable feature of the Stose-Jonas maps is shown along the mountain front northwest of Dryville where a narrow band of Hardyston of the stationary block is in contact and in alignment with a similar band of Hardyston of the "overthrust" block. Discordances in the formations of the "moved" and unmoved block north of Dryville are shown. This area is so deficient in exposures that the writer has no evidence for either proving or disproving the mapping here but doubts whether there is sufficient evidence for definitely fixing the geologic lines and establishing discordant relations.

The similarities of the crystalline rocks in Irish Mountain and those of the transported rocks of the "overthrust" sheet with which they are in contact are not discussed because this phase of the problem has not been investigated sufficiently by the writer. It is worthy of careful study which should be undertaken.

The situation at Irish Mountain requires the splitting of the "overthrust" sheet about an island with one branch going to the northeast and the other to the west. The processes involved are difficult to visualize.

Distinguishing the wedge of which Irish Mountain is a part from other adjoining areas appeals to the writer as impossible. If they originally belonged to regions 15 or more miles apart one should certainly expect more differences. The similarities of the rocks and the structures of the "overthrust" and overridden blocks are so great as to make questionable their conclusion. Their maps show similar slivers of Hardy-

FIGURE 11.—*Portions of the topographic maps of Reading and Boyertown quadrangles*

Showing physiographic similarities between the Irish Mountain mass and the adjoining mountains. According to the "overthrust" hypothesis the Irish Mountain area rose as an anticline in front of the moving "overthrust sheet" and blocked it. Scale: 1 inch = 2 miles.

ston dipping to the north or northwest and bounded on one side by a normal fault within the pre-Cambrian rocks of both blocks, and these patches agree closely in trend.

The writer does not intend to leave the impression that he recognizes no anomalous conditions existing along the flanks of the mountains composed mainly of pre-Cambrian crystalline rocks or that he believes the structural relations are everywhere regular and simple. For example, the Hardyston is absent in places, and if exposures were sufficiently abundant other formations might be missing. Also, discordant dips and strikes are common. These have been interpreted as due to complicated folding, numerous normal faults, and local overthrusts. These discordances are present throughout the region. They are believed to be local structures.

In the quotations given above it is noted that the Irish Mountain stationary block is called an anticline. The Stose-Jonas map (1935a, Pl. 53) does not show it to be. Instead, only monoclinal structures are indicated, all of the sedimentary formations dipping to the northwest. (*See* Plate 5.) What happened to the other limb of the "anticline"?

In summary, the present close relationships of the "overthrust" sheet and the unmoved block of Irish Mountain, both in the kinds of rocks composing them and in the similarity of structural features, raise doubt of the two blocks having been originally miles apart. Further, the thrust that moved huge masses of rocks on both sides of Irish Mountain must have carried great quantities of the pre-Cambrian rocks miles beyond their present distribution, and although not impossible it seems highly improbable that, in the processes of erosion by which thousands of feet of material have been carried away, the crystallines in advance of the Irish Mountain front would be so completely removed as to bring the present fronts of the two blocks in contact and in alignment. The accumulation of improbabilities can be overcome only by specific evidence, if the hypothesis is to be maintained.

LOCK RIDGE

Lock Ridge is an isolated hill 2½ miles long between Alburtis and Longswamp. It is composed of pre-Cambrian gneiss overlain by Hardyston sandstone on the northern flank. On the southeast side it is bounded by a normal fault that has dropped the Tomstown limestone downward into contact with the gneiss, faulting out the Hardyston completely.

In the original paper Stose and Jonas (1935a, p. 769) state: "Like Irish Mountain, this ridge is an anticline in front of the overthrust, and the quartzite on its flank dips north under the valley limestone." (p. 769)

In 1939 they say: "Recent work in this area by Stose and Jonas has led them to conclude that Lock Ridge and the hill to the west, south-southwest of Longswamp, are klippen of the overthrust, detached by erosion and surrounded by and overlying the limestones of the valley."

The reasons for the change of view concerning Lock Ridge are not given. One infers that they would now say that the Hardyston of Lock Ridge dips toward the limestones of the valley but does not pass under them but terminates abruptly at

about the level of the valley limestone. If that is their opinion, one is justified in asking for the evidence which indicates this discordance.

In the original paper, accordant parallel bands of Tomstown and then Elbrook limestones are shown cropping out in turn to the north of the Hardyston outcrop. It is unlikely that the block of gneiss and sandstone would move for miles from the southeast and come to rest in a position of such complete accordance.

The isolated hill of pre-Cambrian gneiss and Hardyston sandstone west of Longswamp is closely similar to Lock Ridge in all respects.

MT. PENN AND DEER PATH HILL

Rising steeply east of Reading and extending in a straight line for 4 miles to the north-northeast is a prominent ridge. South of a col it is called Mt. Penn and to the north Deer Path Hill.

Stose and Jonas (1935a, p. 767) describe the conditions existing here as follows:

"Although Lower Cambrian (Hardyston) quartzite forms the west slope of Mount Penn and Deer Path Hill and dips toward the limestones of the valley in apparent conformable relation, the adjacent limestone is Elbrook and Conococheague and not Tomstown dolomite, which normally overlies the Hardyston quartzite.

"In Deer Path Hill and Mount Penn . . . the quartzite dips west but does not pass under the valley limestones, which are structurally and stratigraphically discordant to it." (p. 762)

The basis for these statements is not given. With no exposures for considerable distances from the foot of these hills, how have these discordances been determined? Even if the closest exposed limestones be assigned to the Elbrook there is still sufficient space for the Tomstown beds to be concealed in the intervening space if they approximate the steep dips of the outcropping Hardyston strata on which they normally rest.

H. Wilkens has called the attention of the writer to some inaccuracies in the Stose-Jonas maps in the vicinity of Reading, one of which seems to have an important bearing on the "overthrust" hypothesis. This is the location of several iron mines along the southwest flank of Mt. Penn. (*See* Figure 12.) These mines are located in the area of Elbrook limestone, close to the "overthrust" fault. If this location is correct, the ore should be limonite, and the occurrence of the deposits in such an association might furnish evidence in support of the "overthrust hypothesis." Actually, the mines yielded magnetite, and the ore bodies were undoubtedly in the pre-Cambrian gneiss, as concluded by D'Invilliers (1883) "though close to the Potsdam" (Hardyston). Previously, Rogers (1858) had described the mines and said that the ore bodies were within the Primal (Hardyston) sandstone. D'Invilliers shows the location of the mines on Sheet XVI of the Atlas accompanying his report. The geographic location of the mines on the D'Invilliers map agrees so well with the ones shown on the Stose-Jonas map that there can be no question but that they are the same.

A portion of Rogers' description is quoted.

"The ore is of the granitoid variety, highly crystalline, containing quartz and feldspar, especially the latter, in great abundance; hornblende and apatite enter also into its composition.

"The principal mine is the vertical shaft of Eckert and Brother: this is sunk 142 feet to the level of a tunnel, which is cut N. 28 feet through rotten sandstone to the top of the vein." (p. 716)

An analysis is given of a specimen of the ore which is called "crystalline magnetic ore, with hornblende, feldspar, quartz, apatite." (p. 717)

The most important point in the quotation is the description of the 142-foot vertical shaft that ended in the Hardyston sandstone 28 feet from the magnetite ore body.

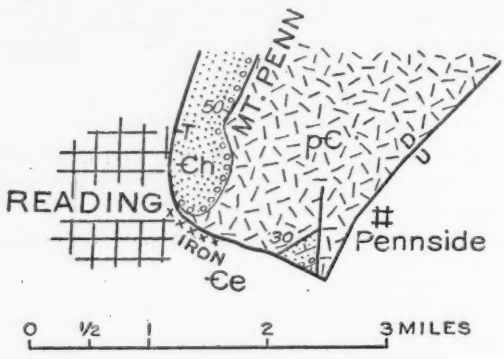


FIGURE 12.—*Portion of the "overthrust sheet"*

(Stose and Jonas, 1935a, p. 766, Fig. 4.) The west and southwest sides of Mt. Penn are shown to be bounded by the "overthrust" fault. A normal (?) fault bounds the mountain on the southeast.

This either indicates that the sole of the "overthrust sheet" is at least 142 feet lower than described by Stose and Jonas or that the Hardyston sandstone of Mt. Penn does pass "under the valley limestones." The latter seems to be the case, and therefore the naming of the hypothetical "overthrust" as expressed in the following statement is unfortunate: "The overthrust fault is here named the Reading overthrust because the thrust relations are clearly shown at Reading." (Stose and Jonas, 1935a, p. 763.)

An additional item is worthy of mention. If Stose and Jonas erred in locating the iron mines in the limestone rather than in the near-by Cambrian sandstone or pre-Cambrian gneiss, it is evident that the mines were close to the edge of the "overthrust" sheet. The sheet here would be so thin that the 142-foot mine shaft should have passed through it and encountered the underlying "overridden" limestones, which it did not do.

Although the exact elevation of the top of the 142-foot shaft is not known, it appears certain that the bottom of the shaft was lower than the limestone outcrops within the city of Reading at 12th and Spruce streets.

RATTLESNAKE HILL

Although considerably beyond the area that has been specifically described as a part of the "Reading Overthrust," it may be well to briefly describe the conditions at Rattlesnake Hill (Fig. 1), along the Delaware River in Durham Township, Bucks County, Pennsylvania. Previous mention has been made of this locality as showing the presence of jasper in a col near the summit of a large high hill of gneiss.

Rattlesnake Hill is composed of pre-Cambrian gneisses. On the north side the gneiss is in contact with Cambrian dolomites exposed near the mouth of Durham

Creek and on the south side with other Cambrian dolomites at Monroe. The situation is similar to those in the Reading region where the advocates of the "Reading Overthrust" hypothesis represent the pre-Cambrian rocks to have been overthrust along a horizontal plane and to have come to rest on Paleozoic rocks.

Rattlesnake Hill, although not specifically mentioned, might well be considered a part of the "Reading Overthrust" since Stose and Jonas (1935) speak of its probable "extension across Pennsylvania to Easton" (p. 763) and across Northern New Jersey into southern New York (p. 777). For this reason the conditions at Rattlesnake Hill are pertinent to this discussion.

Magnetite mines were operated intermittently in the gneiss of these hills from 1727 to 1908. Fackenthal (1937), who was in charge of these mines for a number of years, says that a tunnel was driven into the eastern slope of Rattlesnake Hill, starting a little above the level of Durham Creek, and lower than some of the Paleozoic limestones of the region. The mine which is confined to the gneiss was worked to a depth of 150 feet below the tunnel level. This evidence of the gneiss of the Hill extending approximately 150 feet below the bordering limestones seems to indicate that they are not continuous under the gneiss of Rattlesnake Hill as the "Reading Overthrust" hypothesis would demand.

Rattlesnake Hill is bordered by the Triassic sediments on the south and is the most southerly of the crystalline rock hills of the region. If it is not a part of the overthrust block, there is little basis for assigning any of the crystalline rocks bordering the Delaware River to the "Reading Overthrust."

SEISHOLTZVILLE-SIGMUND-ZIONSVILLE VALLEY

Stose and Jonas show on their maps (1935a, Pls. 52, 53) a narrow limestone "window" that extends in a southwest direction from Zionsville to Seisholtzville and is continuous with the Pine Creek "window" previously discussed.

They (1939) make the following statement:

> "The valley between Seisholtzville and Sigmund contains outcrops of Hardyston quartzite in three small areas. . . . The quartzite at these outcrops is the kind that forms the upper part of the Hardyston and the outcrops are therefore interpreted by Stose and Jonas as anticlines in the limestone." (p. 285)

In their original article (1935a) they say.

> "The upper *Scolithus*-bearing beds of the Hardyston quartzite crop out in anticlines in places on the floor of these intermontane valleys, and there the adjacent lowland is interpreted as underlain by Tomstown dolomite. Several anticlines of the quartzite occur in the valley south and east of Seisholtzville." (p. 771)

The writer has found in this valley pieces of float conglomerate, typical of the basal beds of the Hardyston.

From their detailed map (1935a, p. 772), the section (p. 776), and the above quotations, it appears that this valley was eroded through the overlying "thrust" block and found itself neatly and regularly superposed on an anticline or anticlines of the overridden limestone and Hardyston sandstone. It is a strange coincidence to have a stream start in the overriding sheet approximately 10,000 feet above the present surface and on eroding to the underlying overridden block to find itself

symmetrically located on the top of an anticline trending in the same direction. It could be explained by later adjustment of the stream to underlying structure if the limestone and sandstone anticlines had risen to the old peneplane level. The narrow valley, several hundred feet lower than the tops of the bounding hills which, in turn, are lower than the original peneplane, seems to preclude such an explanation.

The structures in this valley are complex. The Hardyston crops out in a few places, and its presence is determined in others by sandstone and jasper float. Limestone has been quarried near Sigmund and is probably present, although not exposed, in part of the valley floor.

VERA CRUZ VALLEY

The east-west limestone valley in which the village of Vera Cruz (Fig. 1), Lehigh County, is located is also called a "window" by Stose and Jonas. Here also there are most remarkable coincidences if the "overthrust" hypothesis is correct. An examination of their maps (1935a, Pls. 52, 53) shows two patches of quartzite forming part of the "overthrust" block and four patches of the quartzite in the overridden block, all with the same trend as the valley. In one instance a patch of quartzite of the "overthrust" is in contact with a patch of similar dimension and trend in the overridden portion.

On the basis of these quotations, the Hardyston patches of the overridden block would seem to be the tops of anticlines. Also the conglomerate and sandstone symbols of the Hardyston patches of the "overthrust" indicate that they are the southern limb of synclines. This peculiar set of conditions implies the superposition of a syncline or parallel synclines in the overriding block of pre-Cambrian and Hardyston strata immediately above and parallel to an anticline or string of small anticlines in the stationary block. Evidently the stream started in the syncline or line of synclines of the overriding block and when it had cut its way to the bottom found itself on the underlying anticlines in which it has continued to cut its valley. It seems pertinent to remark that superposed streams are normally characterized by lack of adjustment to the structures of the underlying rocks.

Apparently Stose and Jonas have omitted much of the Hardyston from their maps where it was represented only by float material. The Hardyston is probably continuously present on one side and in places on both sides throughout a considerable part of the two valleys described.

Stose and Jonas (1935a, p. 771) state that the valley "windows" are interpreted as the eroded anticlines of the overthrust sheet. The sections given by them (774, 776) show the limestones of the overridden block of these anticlines in several valley "windows," other than those described. Some are below the tops of the existing crystalline rock ridges that bound the "windows," still farther below the old peneplaned surface and thousands of feet or more below the surface when erosion started to wear away the rocks of the "overthrust" sheet. Under these conditions how can one explain the location of the present streams? According to the Stose-Jonas sections, Hosensack, Perkiomen, Pine, and Sacony creeks, Antietam and Manatawny coves, and Sigmund Valley are all nicely situated on the tops of the low anticlines of the thrust plane although the streams must have chosen their present location long before the sole of the "overthrust" was reached by erosion. The low anticlines

of the thrust plane, as shown, do not rise to the level of the tops of the existing hills, and they are evidently considerably lower than the original Schooley Peneplane that beveled them. In the case of Pine Creek valley a syncline in the "overthrust" sheet is symmetrically located above an anticline of the thrust plane (Stose and Jonas, 1935a, Fig. 8C, p. 776).

No coincidences such as those described can be said to be impossible, but a theory that requires the acceptance of so many strains the credulity to a breaking point.

HARDYSTON AS A RIDGE-MAKER

Stose and Jonas (1935a, p. 284) state that "the Hardyston is the most resistant rock in the area and is a ridge-maker"; this is only partly true. In Mt. Penn and Deer Path Hill, where the Hardyston is unusually thick, it extends to the tops of the hills. Even the Stose-Jonas maps and sections show that elsewhere and normally the Hardyston crops out on the flanks of the gneiss hills and generally on the lower slopes. In places the dip of the Hardyston strata is approximately that of the slope of the hill so that they veneer the underlying crystallines and rise high on the hills or even to the summits. Thus, a small thickness of rock may be shown on the map by a relatively wide band. Where the Hardyston is present on the lower slopes of narrow valleys it probably also forms the floor as well. In broad valleys it is likely that the overlying limestones are present even though there are no outcrops.

The recognition of the various structural positions of the Hardyston is important in that it affords a valuable criterion in structural interpretation in places where other criteria are lacking.

NEVERSINK MOUNTAIN, BERNHART HILL, RABBIT HILL, FANCY HILL

At Neversink Mountain and Bernhart Hill near Reading and Rabbit Hill and the nose of Fancy Hill and other exposures in the vicinity of Earlville there is evidence of high-angle, probably normal, faulting, but the exposures are insufficient to determine the actual conditions. It is doubtful whether any two geologists working independently would agree on the location and direction of the faults. Stose and Jonas as well as others seem to have reached the conclusion that normal faults constituting complicated fault systems are present. The writer believes that normal faults with minor and major displacements exist and that they explain the present distribution of the formations and consequently the topographic features. As an illustration, he attributes the isolated eminence of Neversink Mountain as due to the down-faulting of a block of limestone which thus separates it from Mt. Penn and Guldin Hill.

Along Manatawny Creek which separates Rabbit Hill from the main mass of the "overthrust" block east of Oley Valley, the Hardyston sandstone crops out at the creek level dipping steeply to the northwest. The creek here is less than 260 feet above sea level. The sole of the "overthrust" must lie still lower, and yet the Stose-Jonas maps indicate that only a short distance away, both north and south, the sole must be over 300 and possibly 400 feet above sea level.

MYLONITIZATION AND ORIGIN OF JASPER

No discussion of mylonitization is included in this paper since Miller and Fraser (1935) have shown that mylonites are too widely exhibited throughout the region to

be attributed to the "Reading Overthrust." Stose and Jonas (1935b, p. 2039) state "Under mylonitization they [Miller and Fraser] evidently include slickensides and shear planes." There is no justification for this erroneous statement.

The writer also omits detailed discussion of the processes involved in the formation of jasper as this question is believed to have little bearing on the problem and as no additional information has been secured.

RELATION OF THE "READING OVERTHRUST" AND "MARTIC OVERTHRUST"

In view of the fact that an extensive overthrust has also been proposed (Knopf and Jonas, 1929) to explain the complicated geological structures about 30 miles to the south it may be of interest to speak briefly of the relationship between the two. The one lying on the other side of the band of Triassic rocks was named the "Martic Overthrust."

The "Reading" and "Martic" overthrusts as proposed present many similar features although they were assumed to be entirely independent. In each case a great thickness of crystalline rocks, classified as pre-Cambrian, was moved northwestward 15 to 30 miles and came to rest upon younger Paleozoic sedimentary strata. In the case of the "Martic" the roots of the "overthrust" were described as concealed by the Coastal Plain sediments just as the roots of the "Reading" are said to lie beneath the Triassic sediments. In both cases the thrusting is supposed to have taken place during the Appalachian Revolution. In each case intermontane valleys floored with limestone have been interpreted as "windows" which the opponents claimed were not.

The "Martic Overthrust" has been discussed by a number of geologists in articles published between 1929 and 1941. The latest and most exhaustive contribution by Cloos and Hietanen (1941) seems effectively to disprove the existence of a great overthrust in the type locality.

SUMMARY

GENERAL CONSIDERATIONS

The Reading Hills constitute a cluster of hills and ridges in eastern Pennsylvania, extending in a northeasterly direction from a short distance west of Reading to the Delaware River and continuous with the Highlands of New Jersey. These elevations are composed primarily of pre-Cambrian crystalline rocks and minor amounts of Lower Paleozoic sediments.

The distribution and characteristics of these hills were long explained as the result of folding, faulting, and differential erosion. In 1935 a new structural interpretation attributed most of these hills in the Reading region to a great overthrust from the southeast. They were said to constitute the remnants of a great overthrust sheet which moved 15 or more miles and came to rest on Paleozoic sediments, mainly Cambrian and Ordovician limestones.

This paper brings together different lines of evidence that appear to controvert the overthrust hypothesis. Specific data are assembled from all parts of the area, and the bearing on the problem is discussed.

DRILL RECORDS

Drilling was done for water and in the exploration for iron ores. Six localities are described where drill holes were started in the "overthrust" sheet and continued

well below the level where the limestones should have been encountered. In no instance did the drilling reveal this situation. In one instance the lower 900 feet of an iron-ore prospect diamond-drill hole should have been in the overridden limestones, but instead the 1200-foot hole started and ended in pre-Cambrian gneiss. No drilling record has been obtained to indicate Paleozoic limestones underlying pre-Cambrian rocks.

"WINDOWS"

The advocates of the overthrust hypothesis map several "windows" developed by the wearing away of the "overthrust" block, thus exposing the overridden strata, mainly limestones. These are intermontane valleys in part floored with Paleozoic limestone but in other cases developed entirely in the pre-Cambrian gneiss.

Ten of the areas designated as "windows" have been critically examined and are described. The ones selected are considered characteristic. In each case the evidence presented appears to controvert the window interpretation.

PHASES OF THE HARDYSTON

The originators of the "overthrust" hypothesis maintain that a three-fold division of the Hardyston is "constant throughout the area" and that this recognition is essential in the structural interpretation. The writer shows that this condition does not exist and that such data can be of value only locally.

JASPER

The advocates of the "overthrust" interpretation say that "the chert and jasper was produced by silicification of the limestone along the thrust fault." The writer shows that wherever the jasper has been observed in place it occurs in a definite stratigraphic position overlying the sandstone strata of the Hardyston in apparent conformity and where the presence of Hardyston is determined by float the same relationship apparently exists.

Eight specific localities are described. In each the relationships are such as to show that the jasper could not have been formed along a flat thrust plane such as the proposed "Reading Overthrust." The largest masses of jasper are well above the position of the assumed thrust plane, even more than 100 feet higher than the place where the thrust plane is mapped. The jasper is absent where it should be present according to the overthrust explanation and is present in positions inconsistent with that view.

IRISH MOUNTAIN

Stose and Jonas claim that Irish Mountain, composed of pre-Cambrian and Lower Paleozoic strata, was not a part of the "Overthrust" block but is an anticline that rose "out of the limestone in front of the advancing overthrust block" and "blocked its forward movement."

The close similarity of the rocks composing Irish Mountain and the hills adjoining regarded as part of the "overthrust" and other features render such an explanation extremely improbable.

LOCK RIDGE

Lock Ridge and a hill to the west were first described as stationary blocks but in a later article were termed "klippen of the overthrust." The accordance of the pre-

Cambrian and Hardyston of the "overthrust sheet" with the younger formations over which the sheet is supposed to have passed disagrees with the "overthrust" idea.

OTHER LOCALITIES

Other localities are described where the "overthrust" interpretation calls for highly improbable situations. Some of these are Mt. Penn, Deer Path Hill, the Seisholtzville-Sigmund-Zionsville Valley and Vera Cruz Valley.

"MARTIC OVERTHRUST"

The "Reading Overthrust" is compared with the "Martic Overthrust" which lies to the southeast. The same persons have proposed these two overthrusts. The evidence presented in each case is similar. A recent publication seems to disprove completely the existence of a great overthrust in the type locality of the Martic.

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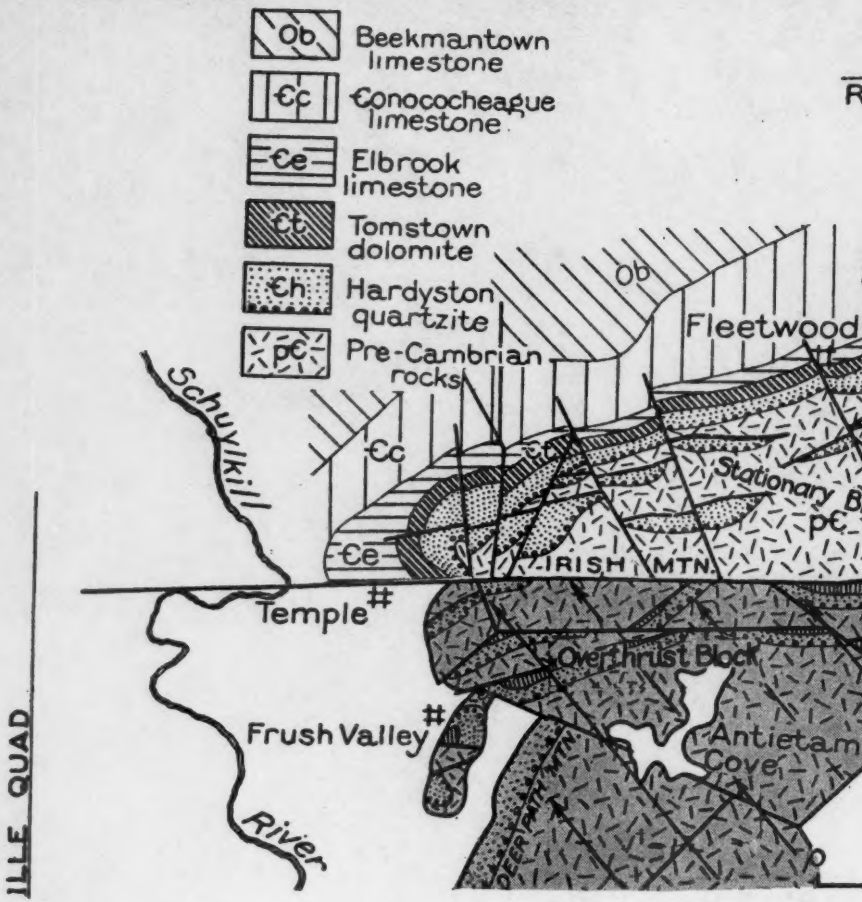
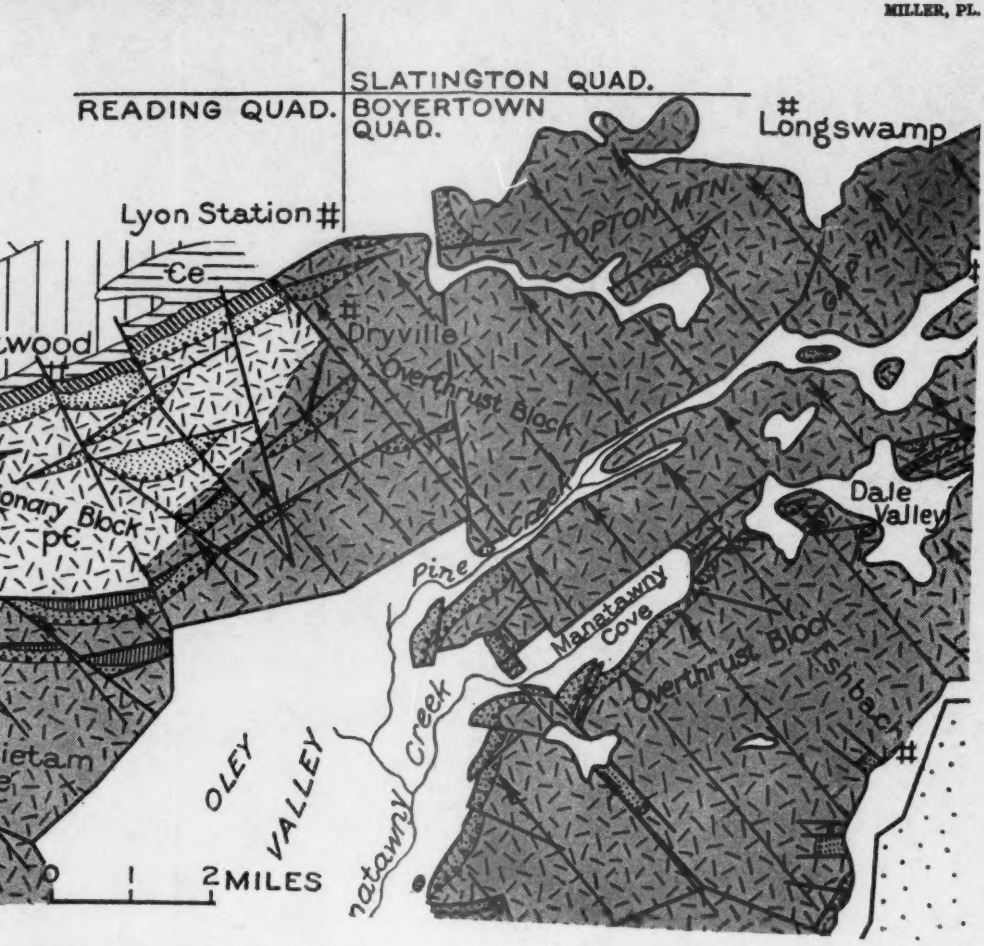


MAP OF POR

Area after Stose and Jonas (1935a, Pls. 52, 53).
"The Irish Mountain anticline . . . apparently rose in front of the advancing
Shading indicates overthrust block.



OF PORTION OF AREA

advancing overthrust and blocked its forward movement." (Stose and Jonas, 1935a, p. 768.)